Hydrology and Earth System Sciences, 4(1), *35–45* (2000) © EGS

Hydrology & Earth System Sciences

Spatial and temporal variations in the occurrence of low flow events in the UK

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Abstract

Information on the magnitude and variability of low river flows at the river reach scale is central to most aspects of water resource and water quality management. Within the UK, river stretches with permanent gauging stations represent less than one percent of the total number of river stretches mapped at a scale of 1:50,000 and fewer that 20% of gauged catchments can be regarded as having natural flow regimes. This has led to the development of simple, multivariate models for predicting average annual natural flow duration statistics through relationships with catchment characteristics. One assumption within these models is that low flows occur at the same time at all points within a catchment, irrespective of the hydrogeological nature and climatic condition of the catchment.

This paper discusses the implications of spatial variations in the timing of low flow events for this type of model. Differences in the timing of the mean day of occurrence of the annual Q95 flow in UK catchments can be identified with low flows occurring earlier in the year within impermeable dry catchments and later in the year for wet permeable catchments. However, any differences in the mean day of occurrence between different catchments are generally masked by the magnitude of the inter-year variability in the day of occurrence.

From analysis of linear combinations of flow statistics from nearest-neighbour gauged catchments, the paper demonstrates that the assumption of temporal coherence of low flows will generally result in an under-estimate of Q95; these underestimates are more significant for pairs of impermeable catchments than for combinations of permeable catchments and impermeable-permeable catchments.

Introduction

There is a considerable variation in river flow behaviour across the United Kingdom over both space and time. The flashy response of wet impermeable catchments in the north and west of the country contrasts markedly with that of an English lowland chalk stream, where flows vary little over the year. At the broadest scale, natural river flow regimes are dependent on precipitation, temperature and evaporation. On a local scale, the natural flows will be controlled by the physical properties of a catchment, including geology, land use and the presence of surface water bodies.

This paper discusses the implications of spatial variations in the timing of low flow events for simple, catchment characteristic based, hydrological models for predicting average annual natural flow duration statistics, implemented within the GIS framework of the Institute of Hydrology's Micro LOW FLOWS software package (Young *et al.*, 1999). Within Micro LOW FLOWS, a digital river network is used in conjunction with digital grids of catchment characteristics to estimate flow statistics describing the natural variability of river flows at ungauged river reaches. Examples of catchment characteristics include soils and the variation of rainfall statistics. The structure of the river network, in conjunction with geo-referenced digital data sets of artificial influences, is used subsequently to identify and incorporate the impacts of artificial influences upon the natural flow statistics. Micro LOW FLOWS is in operational use with all the UK environmental agencies.

International references to techniques for estimating statistics describing the low flow regime at an ungauged reach by models, or rules, relating flow statistics from the same region to physiographic and/or climatic characteristics include Hines (1975) for Arkansas, USA, Nathan and McMahon (1992) for Australia, Pearson (1995) and Clausen and Pearson (1995) for New Zealand. Demuth (1994) gives a comprehensive review of regionalisation of low flows on a world wide scale covering over 120 regression models. The review of the literature did not yield examples of a river network approach equivalent to Micro LOW FLOWS for estimating both natural flow regimes and the impacts of artificial influences upon those regimes.

The 1980 Low Flow Studies Report (Natural Environment Research Council, 1980) was the first major study of the relationships between low flow regimes and physiographic and climatic catchment characteristics in the UK. Subsequently, many regional low flow estimation procedures have been developed for application within the UK. The models incorporated into Micro LOW FLOWS V2.1 are national procedures for predicting natural mean annual and mean monthly flow regimes at ungauged reaches (as represented by flow duration and mean flow statistics) and for incorporating the impacts of artificial influences within the catchment within the estimation procedures. The regional data set used in the development of these models consisted of 865 catchments, which constitutes one of the largest data sets used for regionalisation studies.

The Flow Duration Curve (FDC) represents the complement of the cumulative distribution of daily mean flows over a specific period. Using the FDC, it is possible to identify the percentage of time that any given flow is equalled or exceeded. Within the UK, the variability in observed daily mean flows, and hence the gradient of a FDC, is strongly related to the hydrogeology of a catchment. Furthermore, if low flow statistics are standardised by the mean flow (to minimise the influence of climatic and catchment scale controls), there is a strong relationship between these standardised flow statistics and descriptors of catchment hydrogeology (Natural Environment Research Council, 1980). The statistic used within the Micro LOW FLOWS model to characterise the low flow regime is the period of record Q95 flow, standardised by the period of record Mean Flow (MF), henceforth called the Q95%MF flow. This flow is the flow that is equalled or exceeded for 95 percent of the time. The analysis of UK gauged flow records has demonstrated a strong relationship between the Q95%MF statistic and the gradient of the FDC (Natural Environment Research Council, 1980).

The models for predicting flow statistics are based on a simple conceptual water balance model for estimating MF, and a linear statistical multivariate model for estimating the Q95%MF flow. This model relates the Q95%MF flow to the hydrological characteristics of soils within gauged catchments. Within the UK, these hydrological characteristics of soils are represented by the Hydrology of Soil Types (HOST) classification (Boorman *et al.*, 1995). This classification is a 29 class system in which soils are grouped according to the physical (utilising a qualitative 35 class, classification of hydrogeological units) and hydrological properties of the constituent soil associations. With the development of the Q95%MF model the 29 classes were reduced, based upon the similarity in hydrogeological and low flow response, to 11 groups, termed Low Flow HOST Groups (LFHG) and one additional group, LFHG12, representing the areal extent of lakes. The parameter estimates for the model are summarised in Table 1. and the spatial coverage of LFHG across the UK is presented in Fig. 1. The constituent geological components of the LFHGs are also summarised in Table 1. The model is applied within a catchment by identifying the fractional extents of individual LFHGs within the catchment and taking a linear combination of the parameter estimates for each group weighted by the fractional extent of each group. The performance of the model in explaining the variation in the data set is summarised in Fig. 2. The model tends to over-predict at low values of observed Q95%MF and under-predict at high Q95%MF values. Explaining the full variance of any data set is a problem that is inherent in any modelling exercise.

A potential limitation of the use of the linear model for estimating Q95%MF is that it is assumed that low flows will occur at the same time within a catchment, irrespective of the hydrogeological nature and climatic condition of the catchment. Whilst this may not be a problem in small catchments that are more likely to be hydrogeologically homogenous, it is unlikely to be the case in larger catchments. Thus, within the UK Thames basin above Teddington lock (9948 km^2), the Q95 (or Q95%MF) flows measured at sub-catchment gauging stations do not all occur at the same point in time; the permeable chalk catchments experience low flows later in the year than the impermeable clay catchments within the basin.

The procedure for deriving the long-term flow duration curve at an ungauged reach utilises the estimate of Q95%MF (as described above) to select a flow duration curve (standardised by the mean flow) from a family of type curves. The detail of the estimation of the flow duration curve and mean flow is not the subject of this paper. The models for annual flow statistics are presented in detail by Gustard *et al.* (1992). Young *et al.* (1999) summarise all of the models implemented within Micro LOW FLOWS; these include models for estimating monthly flow statistics.

The two principal objectives of the study described in this paper were to:

1. Investigate the importance of hydrogeological and climatic controls on the mean time of occurrence and the inter-year variation in the time of occurrence of the annual Q95 flow in UK catchments.
2. Quantify the effect of differences in the mean time of occurrence of the annual Q95 flow on the precision of Q95 flows estimated using a model that assumes temporal coherence of flows within a catchment.

To meet these objectives, daily mean flow data from a subset of the 865 graded catchments were used to assess:

1 The regional differences in the time of occurrence of annual Q95 flows (objective 1)
2 Physical controls on the mean time of occurrence of annual Q95 flows (objective 1)

Table 1. Q95 estimates for Low Flow HOST Groups (LFHG) and constituent hydrogeological units

LFGH	Q95 (%MF)	Std. Error	Contituent HOST classes	Description of Hydrogeological Units
1	40.8	1.7	1	3 Chalk, chalk rubble, 23 Clay with flints or plateau drift, 26 Chalky drift
2	31.9	2.6	29	4 Soft Magnesian, brashy or Oolitic limestone and ironstone
3	65.7	2.9	3	1 Soft sandstone, weakly consolidated sand, 19 Blown Sand, 24 Gravel, 34 Sand
4	25.0	3.0	2,4	2 Weathered/fissured intrusive/metamorphic rock, 5 Hard fissured limestone, 13 Hard fissured sandstone
5	49.0	6.8	5,12	1 Soft sandstone, weakly consolidated sand, 2 weathered/fissured intrusive/metamorphic rock, 3 Chalk, chalk rubble, 4 Soft Magnesian, brashy or Oolitic limestone and ironstone 13 Hard fissured sandstone, 18 Colluvium, 20 Cover loam, 25 Loamy drift, 26 Chalky drift
6	6.5	5.6	6, 7, 8, 9, 10	1 Soft sandstone, weakly consolidated sand, 2 Weathered/fissured intrusive/metamorphic rock 3 Chalk, chalk rubble, 7 Hard but deeply shattered rocks, 14 Earthy peat, 15 River alluvium 16 Marine alluvium, 17 Lake marl or tufa, 19 Blown sand, 20 Coverloam, 22 Till, compact head, 24 Gravel, 25 Loamy drift, 26 Chalky drift, 34 Sand
7	10.7	0.8	13, 15, 16, 17, 18, 20, 21, 23	2 Weathered/fissured intrusive/metamorphic rock, 6 Hard coherent rocks, 7 Hard but deeply shattered rocks, 8 Soft shales with subordinate mudstones and siltstones, 9 Very soft reddish block mudstones (marls), 11 Very soft bedded loams, clays and sands, 12 Very soft bedded loam/clay/sands with subordinate sandstone, 18 Colluvium, 20 Coverloam 21 Glaciolacustrine clays and silts, 22 Till, compact head 23 Clay with flints or plateau drift, 25 Loamy drift 27 Disturbed ground, 35 Cryogenic
8	1.1	2.0	19, 22, 24	10 Very soft massive clays
9	15.0	2.2	14	1 Soft sandstone, weakly consolidated sand, 2 Weathered/fissured intrusive/metamorphic rock 5 Hard fissured limestone, 7 Hard but deeply shattered rocks, 13 Hard fissured sandstones, 18 Colluvium, 24 Gravel, 25 Loamy drift
10	6.8	1.5	11, 25, 26, 27, 28	2 Weathered/fissured intrusive/metamorphic rock, 15 River alluvium, 19 Blown sand, 24 Gravel, 44 Raw peat
11	29.4	2.1	97	Unsurveyed/Urban
12	65.1	25.8	98	Lake
R^2=	0.573			Standard Error = 7.427

3 The statistical significance of differences in the mean time of occurrence of annual Q95 flows between nearest-neighbour catchments (objective 1).
4 Implications of variations in the mean time of occurrence of annual Q95 flows for linear multivariate models for predicting Q95 flows (objective 2).

A total of 388 catchments from 865 was selected for the study. The flow records for these catchments were of good hydrometric quality, unaffected by significant anthropogenic influences (such as impounding reservoirs, discharges and abstractions) and covered the period 1976 to 1995. The criteria for assessing hydrometric quality and

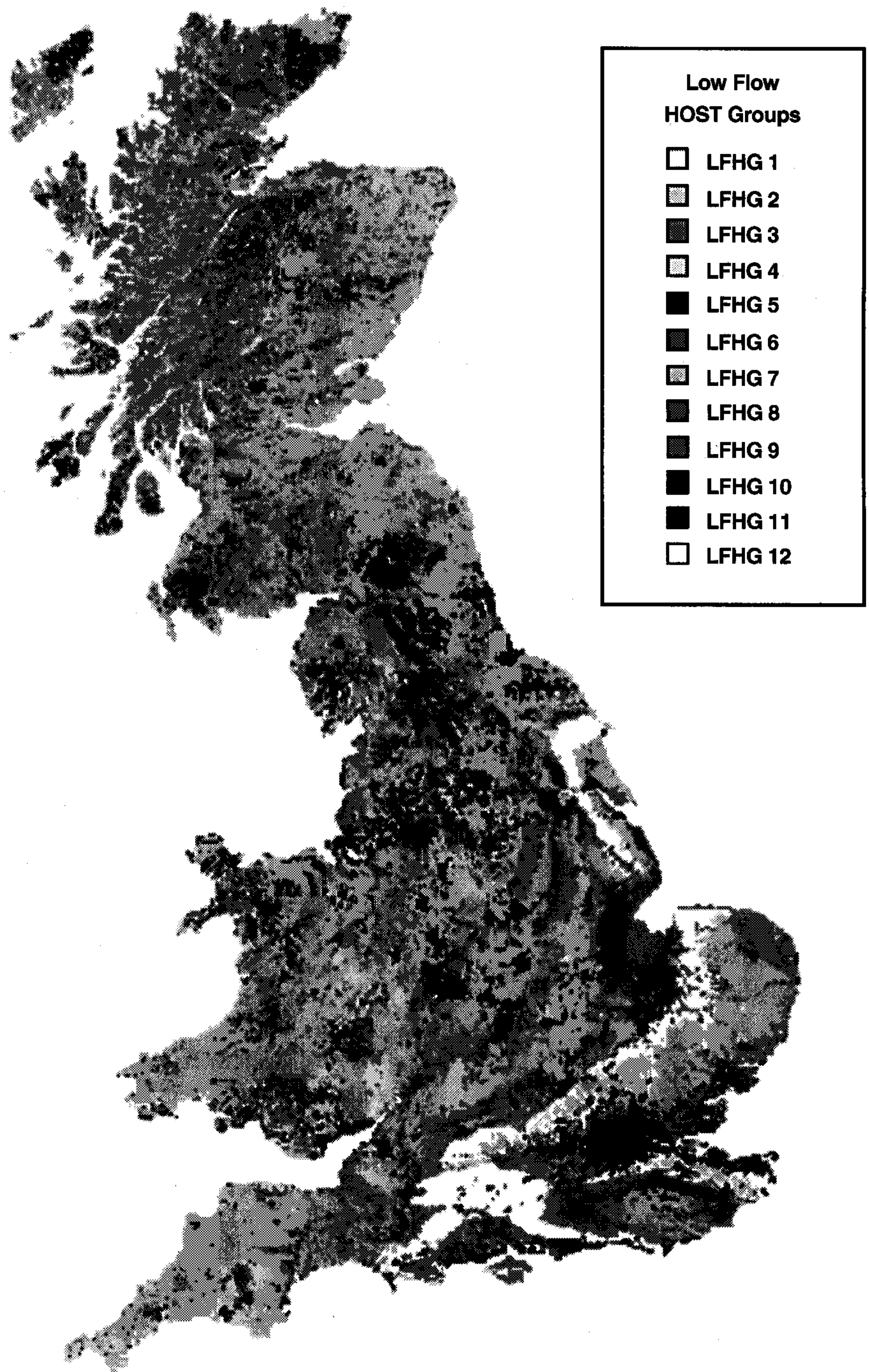

Fig. 1. *Map of Low Flow HOST Groups within a 1 km cell across the UK.*

degree of artificial influence are described by Gustard *et al.* (1992).

Derivation of the mean day of occurrence of annual Q95 flows

For each of the 388 catchments, the days on which the annual Q95 occurred were extracted over the period of record. It is worth noting that the mean of the annual Q95 will not be as extreme as the long term Q95 derived from the full period of record. For the catchments used in this study, the long term Q95 flow was on average 80% of the mean annual Q95. Circular statistics (Mardia, 1972) were employed to calculate the mean day of occurrence and the inter-year variation in the day of occurrence. This approach

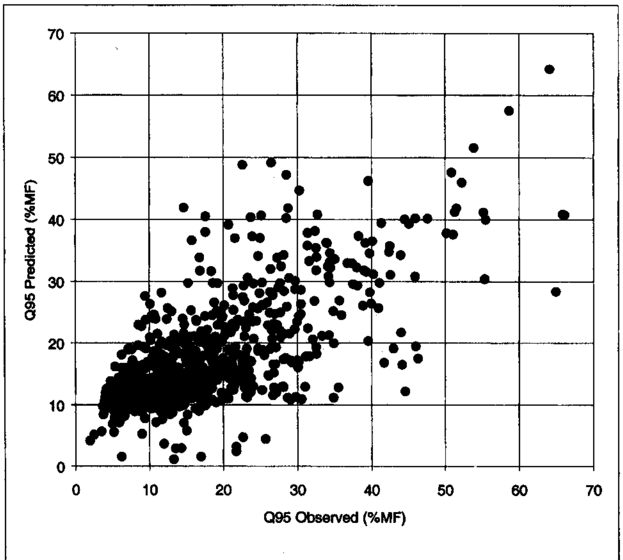

Fig. 2. *Predictive performance of the Q95 model.*

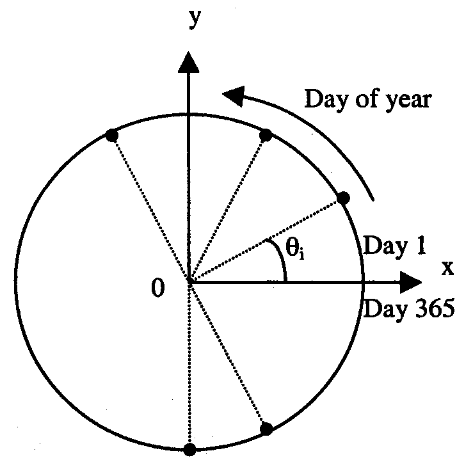

Fig. 3. *Calculating the mean Q95 day using directional statistics.*

was adopted to address the potential problem of calculating the mean when the day of occurrence lies close to the end or the beginning of a calendar year. Thus, the 31st of December and the 1st of January are adjacent in the time series but are not considered as such if day numbers from 1 to 365 are used. The day number mean of these dates would lie between day 182 and 183 (within a non-leap year) rather than between day 365 and day 1. Using circular statistics, the mean day of the Q95 and the corresponding standard deviation are calculated by expressing the day number as an angle:

$$\theta_i = \left((\text{ day of occurrence }) \times \frac{2\pi}{\text{LENYR}} \right) \quad (1)$$

where: LENYR is 365, or 366 for a leap year.

From the x-axis, the angles are calculated in an anti-clockwise direction (Fig. 3). The days are expressed as weights of unit mass, sited on the circumference of a circle of unit radius, from which the centroid can be found by resolving the x and y components and calculating the mean of the respective components over the value extracted for each year within the period of record:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \cos\theta_i \qquad \bar{x} = \frac{1}{n}\sum_{i=1}^{n} \sin\theta_i \quad (2)$$

The mean direction is therefore given by:

$$\bar{\theta} = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) \quad (3)$$

If $\bar{\theta}$ is negative then 2π should be added to $\bar{\theta}$. The mean direction is then changed back to a day number to yield the mean day of occurrence using:

$$\text{MQ95D} = \left(\bar{\theta}.\frac{\text{LENYR}}{2}\right) \quad (4)$$

The inter-year variability, or spread about the mean Q95 day is given by the mean resultant ($\bar{r}$):

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2} \quad (5)$$

As $\bar{x}^2$ and $\bar{y}^2$ can only lie between 0 and 1 the value of $\bar{r}$ will always lie between 0 and 1. When $\bar{r}$ approaches unity then the timing of the Q95 is strongly seasonal with little inter-year variability in the timing of the day of occurrence. A small value of $\bar{r}$ indicates a large inter-year variability in the time of occurrence of the annual Q95 and thus the value of the mean Q95 day is less meaningful. The standard deviation, S_o, is defined, in radians, as:

$$S_o = \sqrt{-2\ln\bar{r}} \quad (6)$$

This can be converted to a standard deviation, in days, by:

$$\text{SDQ95D} = S_o\left(\frac{365}{2\pi}\right) \quad (7)$$

Analysis of the spatial variation in the mean day of occurrence of the annual Q95 flow

Figure 4 presents the mean Q95 day and the mean resultant for each catchment on a map of the UK. The mean resultant was used, as opposed to the standard deviation, to give visual weight to those stations that have strong seasonality of low flow events. The mean day of occurrence of the Q95 is indicated by the direction of the tail and the strength of the

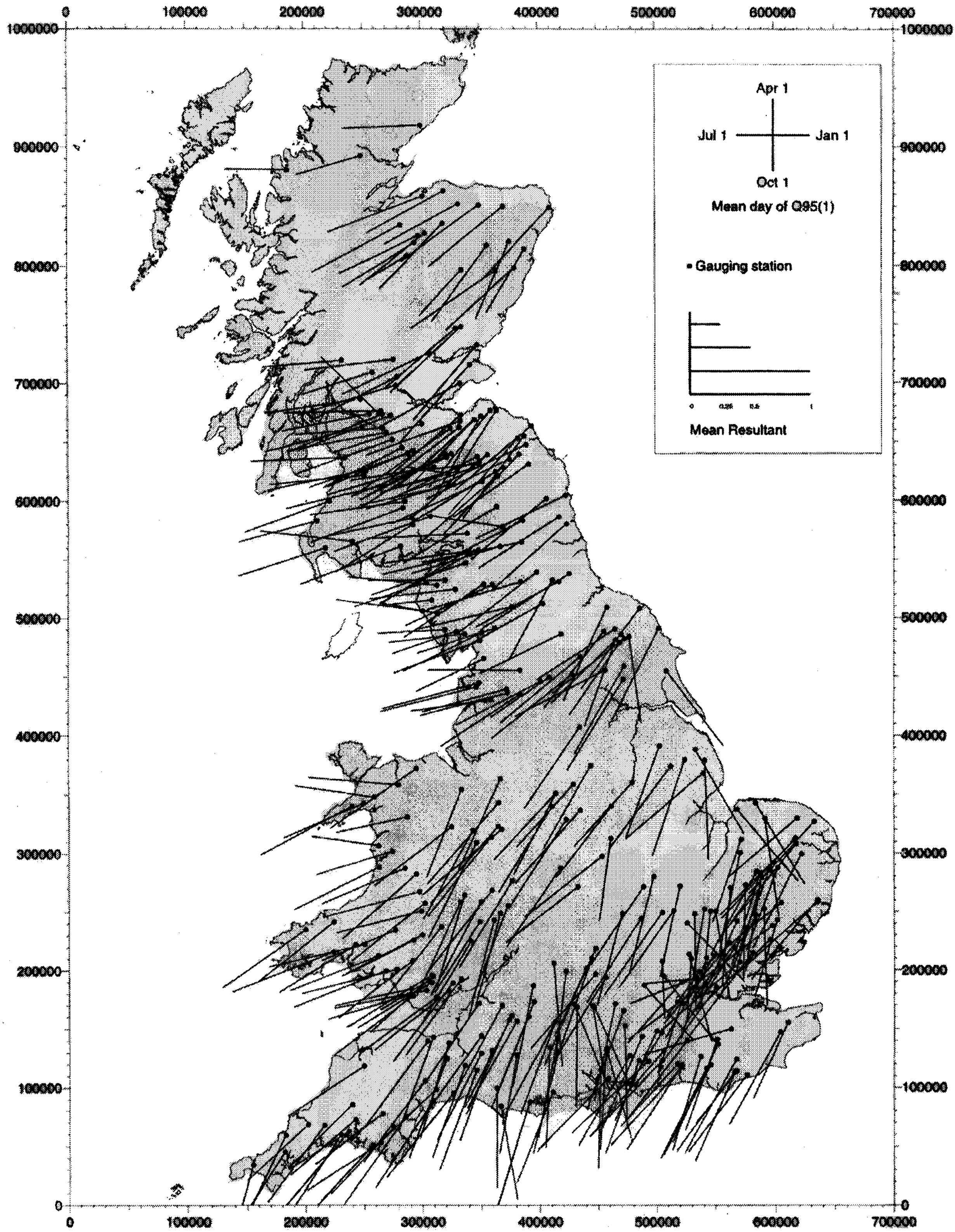

Fig. 4. *Seasonality of occurrence of the mean Q95 day.*

seasonality is indicated by the length of the tail. The longer the tail the smaller the between year variability in the timing of low flows. The lengths of the tails in Fig. 4 indicate that, for most of the catchments considered, the time of occurrence of the annual Q95 is strongly seasonal with most catchments experiencing low flows between mid-summer and the end of the autumn.

The UK has a temperate maritime climate. UK low river flows occur after an absence of rain as the depth of water held in storage within the catchment is depleted. The depletion of this storage, in natural systems, is a function of water in storage (determined by precipitation input and evaporative losses) and drainage from storage (influenced by catchment characteristics like soil, geology and topography). One exception to this is the locking up of water as snow in winter which may result in the lowest flows being observed during the winter. Although this is not a common phenomenon in the UK, it can occur in some high catchments in the north of Scotland.

In the north and west, where catchments are characterised primarily by impermeable geologies as represented by the occurrence of LFHG class six (Fig. 1) and other impermeable classes, the lowest flows tend to occur in early July when evaporation losses are high. Annual Q95 flows that occur in the autumn can be associated with the unconfined chalk of southern England (LHOST1). Figure 4 indicates that there is more variability in the mean day of occurrence of the low flows between gauging stations in areas of more permeable geology, which demonstrates the complex controls of the hydrogeology relating to storage and release of water from storage in these permeable systems.

To understand further the climatic and hydrogeological controls on the timing of UK low flows, linear stepwise multivariate regression analysis was used to identify the most important variables that determine the mean day of occurrence of the Q95 flow. Controlling variables identified as potentially important were:

- Base Flow Index (BFI). The BFI is the ratio of the volume of water derived from the slow flow component of a hydrograph to the total volume of water over a specified period of record and is a good measure of the permeability of a catchment. The BFI was calculated for each catchment from the gauged flow data using a hydrograph separation algorithm described in (Natural Environment Research Council, 1980). The use of BFI as an independent variable is not rigorous as both BFI and the MQ95D are derived from stream flow data. The use of BFI is justified as it is demonstrably related to catchment hydrogeology (Natural Environment Research Council 1980), and the objective of the regression modelling was to identify controls on the timing of MQ95D rather than to develop a predictive model.
- Catchment average Standard period Average Annual Rainfall (SAAR) 1961–1990. These estimates were derived from a map produced by the UK Meteorological Office (Spackman, 1996) gridded to a 1km resolution. SAAR is a measure of how wet the catchment is and is a useful surrogate for the seasonal variation in rainfall across the UK in which a greater seasonality in rainfall is observed in the wetter north and west of the country.

The results of a multivariate regression analysis between the mean day of occurrence and the independent variables BFI and SAAR are summarised in Table 2. BFI accounts for almost 50% of the explained variance and is the dominant factor influencing the mean day of occurrence of the Q95 (as BFI increases the mean day occurs later within the year), whilst SAAR accounts for less than 20%. The parameter estimate for SAAR is negative which implies that in wetter catchments the mean day of occurrence of the annual Q95 is earlier in the year. Given that the Pearson correlation between BFI and SAAR is 0.4 (the wetter areas of the UK tend to be more impermeable) SAAR may be a surrogate for other hydrogeological influences. Other characteristics, including topographic characteristics such as catchment area and mean catchment slope, were also investigated but were not found to be significant, in part due to the strong inter-correlation between some of these characteristics. This regression analysis confirms the controlling influence that hydrogeology has on the time of occurrence of UK low flow events.

Table 2. Multivariate regression results for mean day of occurrence of Q95

Significant variables	Partial R^2	Model R^2	Parameter estimate
INTERCEPT			218.445
BFI	0.4776	0.4776	72.031
SAAR	0.1759	0.6534	−0.0250
model standard error	17.01		

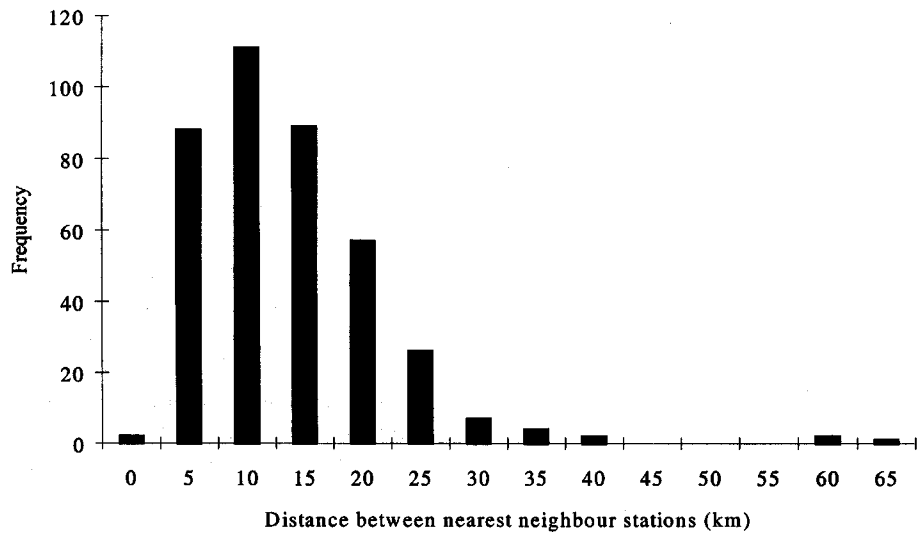

Fig. 5. *Histogram of distances between nearest-neighbour stations.*

Evaluation of differences in the mean time of occurrence of annual Q95 flows between nearest neighbour catchments

Considering the inter-year variability in the timing of the annual Q95, one important consideration for the regionalisation of low flow statistics is whether the variations in the mean time of occurrence are significant. To evaluate this, each of the 388 stations was paired with its nearest neighbour (based on closest distance) to explore the variations in the timing of the Q95 that occur over small geographic distances. A histogram of the distance between these nearest-neighbour stations (Fig. 5) shows that approximately 90% of the paired catchments lie within 20km of each other. Approximately 90% of the paired catchments had a difference in BFI of less than 0.2 and a difference in SAAR of less than 350mm.

Two tailed t-tests were used to determine whether, on average, the Q95 occurred on significantly different days within the two catchments in each pair. The assumption is made that the two independent samples originate from T distributions $T(\mu_1, \sigma_1^2)$ and $T(\mu_2, \sigma_2^2)$. The null hypothesis $H_0{:}\mu_1=\mu_2$ tested is that on average the Q95 occurs on the same day in the two catchments in each pair. The test statistic used was based on the assumption of equality in the variances of the two sample populations. These T-tests indicated that only two pairs of stations had significantly different mean days of occurrence (Table 3).

The first pair of deviant catchments is located in the county of Essex in East Anglia and represents two of the driest gauged catchments in the UK, where the annual runoff is approximately $100mm^{-1}$ yr. In these catchments, the timing of the Q95 flow is more likely to be driven by subtle climatic/land or water use factors as opposed to the hydrogeological response. The second pair of catchments is located either side of the Pennine divide in northern England on karst limestone. These catchments may have significantly different days of occurrence of Q95 because one of the catchments has an area of only 1.5 km^2 and so may be influenced by localised storage mechanisms within the limestone that are averaged out in the larger catchment. The inability to determine significant differences in the time of occurrence between the majority of nearest-neighbour catchments reflects the relatively large inter-

Table 3. Summary information for station pairs with significantly different mean days of occurrence for Q95

Nearest Neighbour stations	SAAR (mm) (1941–1970)	Catchment Area (km^2)	BFI	Distance between nearest neighbour stations (km)
Pair 1 36003	602	54	0.63	6.48
36005	602	156	0.46	
Pair 2 23011	1401	59	0.33	
76011	1163	1.5	0.19	17.60

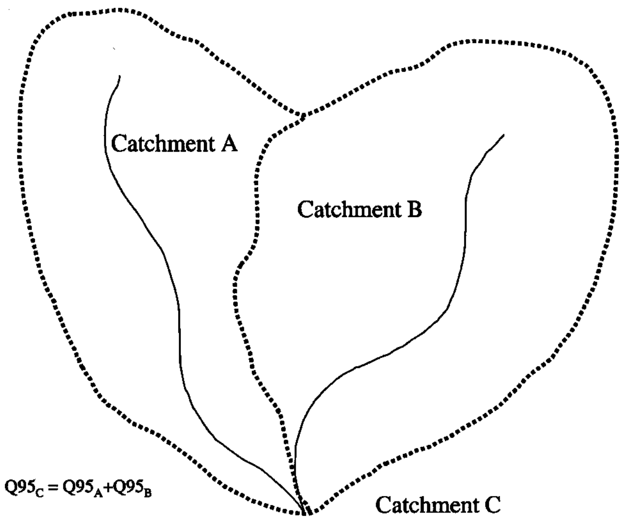

Fig. 6. *Hypothetical catchment configuration demonstrating the calculation of mean annual Q95 under scenario one.*

year variability in the day of occurrence of the Q95 flow within a year and the fact that there are only relatively small differences in SAAR and BFI between the paired catchments.

The implications of variations in the mean time of occurrence of annual Q95 flows for the linear multi variate regression models for predicting Q95 flows

It has been demonstrated that there is a significant relationship between the mean day of occurrence of the Q95 flow within a catchment and the rainfall and hydrogeological characteristics of the catchment. However, in the context of the inter-year variability, the differences in the mean day of Q95 occurrence between nearest neighbour catchments are generally not significant. The ultimate concern of the study was to determine the implications of assuming that the Q95 is temporally coherent over all parts of the upstream network for linear, statistical modelling of flows. To evaluate this, a hypothetical catchment was constructed for each pair in which the catchment pair (catchments A and B) are assumed to be a sub-catchment of a larger catchment, catchment C (Fig. 6). The flow for catchment C is assumed to be a linear combination of the flows from the sub-catchments A and B. Three scenarios were considered:

1. The annual Q95 occurs on average on the same day throughout the river network and thus the Q95 flow for catchment C can be estimated using the sum of the mean annual Q95 flows from sub-catchments A and B.
2. The Q95 flows in the sub-catchments are not temporally coherent and the flow at C is the sum of the Q95 flow from sub-catchment A and the flow which occurs in sub-catchment B when sub-catchment A experiences a Q95 flow.
3. The Q95 flows in the sub-catchments are not temporally coherent and the flow at C is the sum of the Q95 flow from sub-catchment B and the flow which occurs in sub-catchment A when sub-catchment B experiences a Q95 flow.

In each case, the Q95 was expressed as runoff with units of mm yr $^{-1}$, thus minimising the influence of catchment area on the scale of the runoff processes in each catchment. Under scenario one, the Q95 flows in each sub-catchment

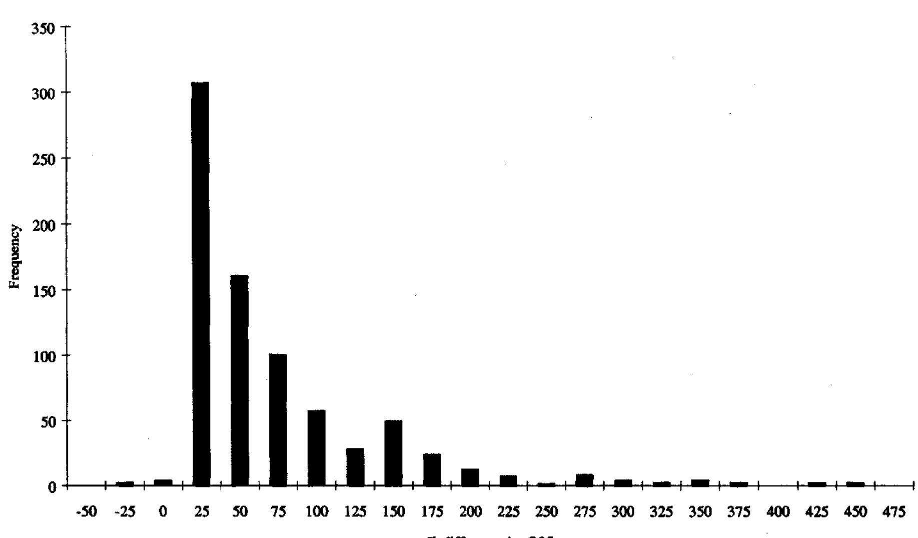

Fig. 7. *Frequency distribution of differences in Q95 between scenario one and scenarios two and three.*

were summed. Under scenario two, the mean annual Q95 in sub-catchment A was added to the mean of the flows that occurred in sub-catchment B on the mean Q95 day of sub-catchment A, and vice versa for scenario three. For example, if the mean day of occurrence of the annual Q95 flow for sub-catchment A occurred on day 250 then the corresponding average flow on day 250 was calculated from the whole time series for sub-catchment B.

These scenarios were evaluated for all catchment pairs. Since scenario one is the assumption used in the current Q95 estimation procedures within Micro LOW FLOWS, the Q95 derived under this scenario was used as a benchmark to determine the percentage difference between the Q95 flows derived under scenario one and scenarios two and three. Figure 7 shows the frequency distribution of the percentage difference between the Q95 derived using scenario one and the Q95 derived using scenarios two and three.

Figure 7 demonstrates that the distribution of percent differences in the Q95 is highly skewed. The median difference is 33.78 percent, and the 68% and 95% confidence intervals are (12.60, 114.56) and (4.11, 255.23) percent respectively. Only three values of Q95 derived using scenario two or three are smaller than the Q95 derived using the scenario of temporal coherence. Hence the flow in sub-catchment B is likely to be higher than the mean annual Q95 flow for sub-catchment B on the mean day of occurrence of the annual Q95 flow for sub-catchment A and vice versa. As scenarios two and three are more representative of reality, the Q95 derived under scenario one (temporal coherence) will almost always result in an underestimate of the actual Q95 for catchment C.

For each pair, the percentage differences observed between scenarios two and three and scenario one are plotted in Fig. 8a as a function of the average BFI for the pair. These percentage differences are also plotted as a function of the difference in BFI between the pair in Fig. 8b. The percentage differences increase with lower average BFI (Fig. 8a); catchments that have a low BFI also have a high day to day variation in runoff. A small time shift can imply a high change in flow, whereas a more permeable catchment shows less variability and is therefore less sensitive to the time of occurrence. This behaviour is accentuated in Fig. 8a as a given difference in the flows estimated under scenario two or three and scenario one will represent a larger percentage difference of the flow derived under scenario one in these impermeable, low Q95 catchments. Figure 8b illustrates that the percentage error when taking a linear combination of the Q95s from an impermeable and permeable catchment is lower than taking a linear combination of the Q95s from two impermeable or two permeable catchments. This is despite demonstrable differences in the mean day of occurrence of Q95 flows between permeable and impermeable catchments. This is explained by the fact that the Q95 estimated for catchment C will be dominated by the much larger Q95 flow of the permeable catchment.

Summary

This paper has demonstrated that differences in the timing of the mean day of occurrence of the annual Q95 flow in UK catchments can be identified with low flows occurring earlier in the year within impermeable dry catchments and later in the year for wet permeable catchments. When considering the inter-year variability in the timing of the annual Q95 flow, significant differences do occur in the mean timing of low flows between catchments with very

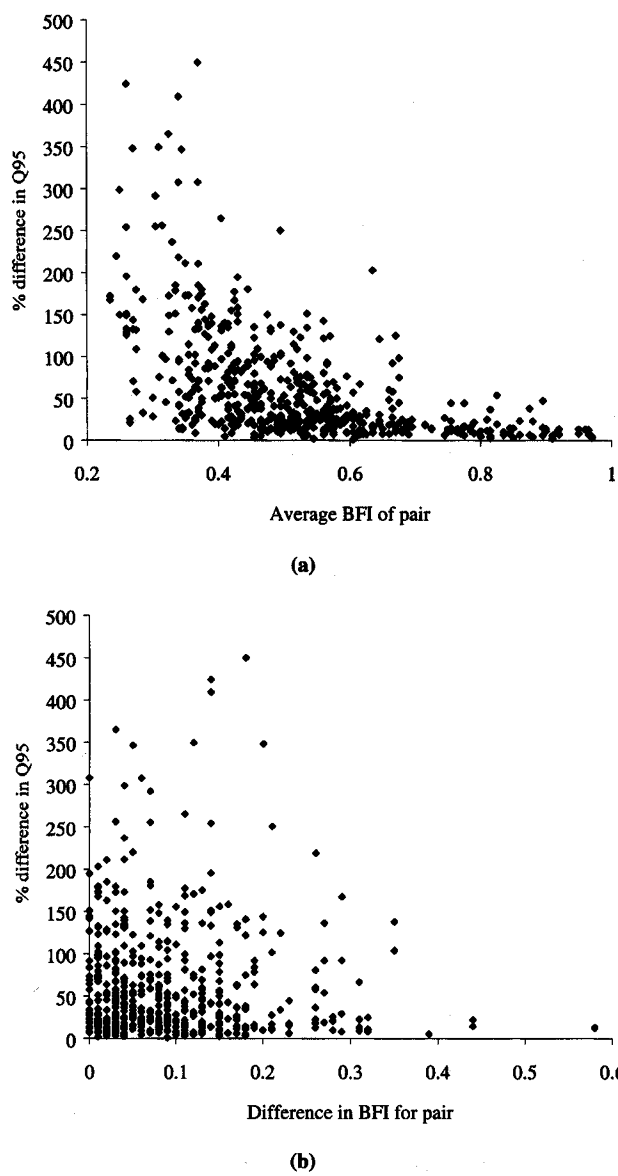

Fig. 8. *Differences in Q95 between scenario one and scenarios two and three as a function of BFI characteristics.*

different hydrogeological characteristics but these differences are not observed in the majority of nearest-neighbour stations because of the similarity in rainfall and hydrogeological regimes observed in nearest-neighbour pairs. Any differences in the mean day of occurrence are masked by the magnitude of the inter-year variability in the day of occurrence compared with the between catchment differences in the mean day of occurrence.

Regional models for predicting a Q95 flow statistic for a catchment are normally based upon linear combinations of Q95 flows for either lumped sub-catchments or gridded values. These models assume that low flows are temporally coherent over the catchment for which flows are being estimated. Analysis of linear combinations of flow statistics from nearest-neighbour gauged catchments has demonstrated that this assumption of temporal coherence of low flows will generally result in an under-estimate of Q95. These underestimates are more significant for pairs of impermeable catchments than for combinations of permeable catchments and impermeable-permeable combinations.

Although significant differences exist between the timing of the Q95 flows in impermeable and permeable catchments, these do not lead to a high numerical error in the combined Q95 flow when linear combinations are taken of these catchments using the assumption of temporal coherence. This is a consequence of the base flow of the combined catchment being dominated by the contribution from the permeable catchment.

The under-estimation of Q95 in flashy impermeable catchments, resulting from the assumption of temporal coherence, does not conform to users' views that generally the linear Q95 model within the Micro LOW FLOWS tends to over-estimate Q95 rather than under-estimate in this type of catchment. This may reflect the inability of the regression model to model the full range of observed Q95 flows within the data set. The regression model tends to over predict in low Q95 catchments which more than compensates for the under-estimation caused by the assumption of temporal coherence of Q95 flows within a catchment.

Acknowledgements

The Authors would like to thank the Environment Agency for England and Wales and the Natural Environment Research Council for their financial support of this study.

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