Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme

Improving the FEH statistical procedures for flood frequency estimation

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Steve Killeen

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Head of Science

Executive summary

This report recommends changes to the procedures contained in the Flood Estimation Handbook (FEH), which have been adopted as standard practice by the principal bodies engaged in flood frequency estimation in the UK and, in particular, by the Environment Agency. These procedures provide estimates of the flows that will occur in rivers on moderately rare occasions: flow values that have an exceedance probability in any given year of 50 per cent (a 2-year return period) to 1 per cent (a 100-year return period), or even more rare. In the majority of cases where such estimates are required, the locations affected will be ungauged and too far from established river gauging stations to provide data records that can be immediately transferred.

The changes recommended arise, in part, because the HiFlows-UK project has led to the creation of a much-improved database of systematically recorded flood data. Not only are the data records now much longer than those used previously but the HiFlows-UK project put substantial effort into the quality control and assessment of the whole data-set. This means that the data available for analysis have been dramatically improved. Another influence on the renewed procedures has been feedback from users of the FEH, both informal and formal. Without substantially changing the overall framework of the methodology, most technical details of the method have been updated to improve the performance of the procedure. The updates include significant improvements to the theoretical statistical framework underlying the method.

In addition, it has been possible to consider some new descriptors of catchment topography and local climate that have been proposed since the FEH study. In particular, a new descriptor that measures floodplain extent has been devised and is now included in the improved procedures.

This report is largely a technical description of the studies that have led to the new recommendations. The folllowing are the key improvements.

- A new regression model for estimating the median annual maximum flood (QMED) at ungauged catchments (Chapter 4).
- An improved procedure for the use of donor catchments for estimation of QMED at ungauged catchments (Chapter 5).
- An improved procedure for formation of pooling groups and estimation of pooled growth curves (Chapter 6).

Flood estimates produced by the new procedures can be substantially different from those produced using the original FEH procedures. On taking the catchments whose data have been analysed as typical examples, and treating them as if they were ungauged, the ratios of the new estimates to the FEH estimates indicate the following changes.

- The changes in QMED range from 0.55 to 2.01, with half being greater than 1.15 (25 per cent of the ratios are less than 1.00, and 25 per cent are greater than 1.24).
- For floods with an annual probability of exceedance of 1 per cent (the 1 per cent flood), the changes range from 0.48 to 2.24, with half being greater than 1.14 (25 per cent of the ratios are less than 0.97 and 25 per cent are greater than 1.32).

For both QMED and the 1 per cent flood, the new procedure produced lower estimates than the FEH in the East of England, whereas increases in both quantities were generally observed in West England, Wales and Scotland.

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The Centre for Ecology and Hydrology (CEH) project team wishes to acknowledge the following people and organisations for assistance provided during the project:

- The Environment Agency HiFlows-UK project for making available the HiFlows-UK data set of annual maximum peak flow and peaks-over-threshold series.
- The Project Steering Group: Paul Webster (Hydro-Logic Ltd), David MacDonald (Black & Veatch), Peter Spencer (Environment Agency), and Kate Marks (Environment Agency).
- Reviewers of the draft report: The Project Steering Group, Stefan Laeger (Environment-Agency), Rob Lamb (JBA Consulting), Duncan Faulkner (JBA Consulting), and Eleanor Heron (Environment Agency).
- Colleagues at CEH, in particular Lisa Stewart and David Morris.

Contents

1 Introduction

This report presents the results of the R&D project SC050050 *Improving the FEH statistical procedures for flood frequency estimation*, funded by the Joint Department for Environment, Food and Rural Affairs (Defra)/Environment Agency Flood and Coastal Erosion Risk Management R&D Programme.

1.1 Statistical flood frequency estimation in the UK

The use of statistical extreme value techniques for flood frequency analysis is a long-established practice in applied hydrology, both in the UK and elsewhere. This section sets the research conducted in the present project in context with regard to the developments of this particular branch of hydrology. For the UK, two key milestones were the Flood Studies Report (FSR) published by the Natural Environment Research Council (NERC, 1975) and the Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999). The hydrological literature contains a vast number of references to the application of various statistical distributions to model annual maximum (AMAX) series of peak flow and, due to the subject's importance, this literature is constantly growing.

1.1.1 Pre-FSR

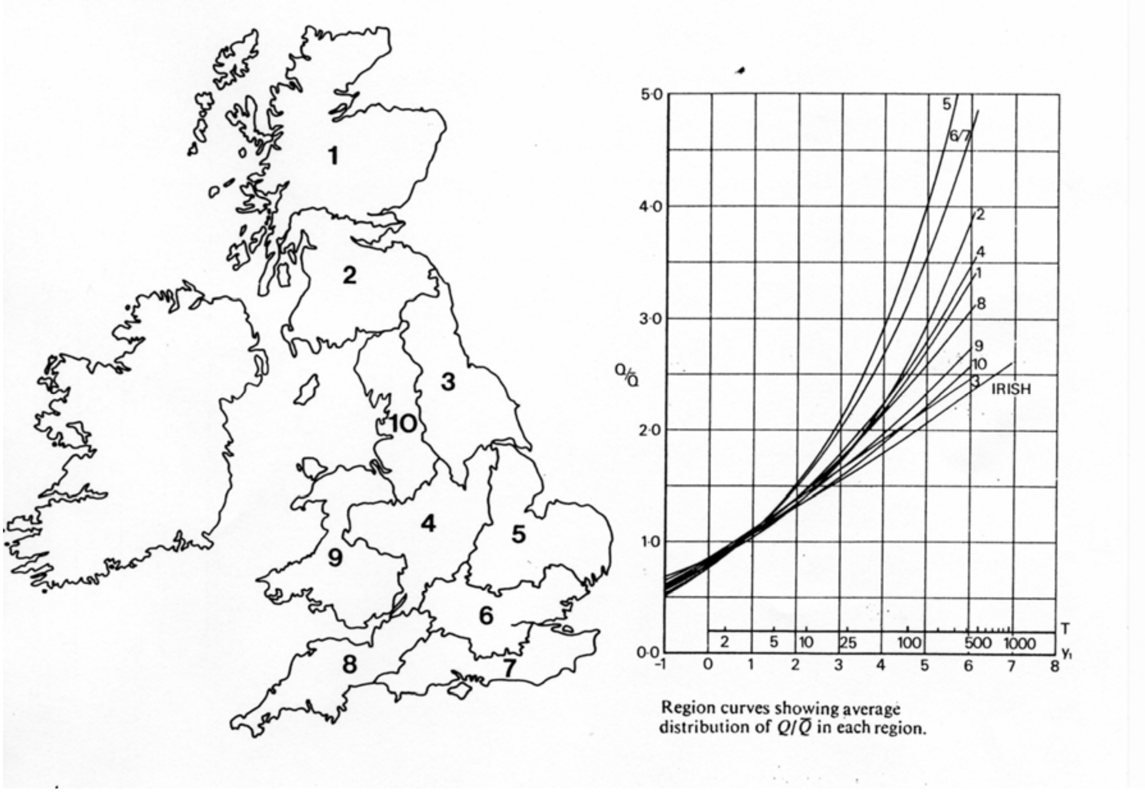
An excellent overview of the state of flood frequency analysis in the UK before the publication of the FSR was provided by Wolf (1965), who traced the use of statistical methods in flood frequency analysis back to the early 20th century (Gore and Thomson, 1909; Horton, 1913, both cited by Wolf, 1965). However, the first systematic application of extreme value theory and models in hydrology is often attributed to Gumbel (1941), who successfully fitted extreme value distributions of Type 1 (Gumbel distributions) to AMAX series of daily mean flow from many countries. Other methodological milestones of importance to the subsequent development of national UK procedures include the publication of the Generalised Extreme Value (GEV) distribution (Jenkinson, 1955) and the development of the index-flood method at the United States Geological Survey (USGS) reported by Dalrymple (1960).

1.1.2 Flood Studies Report

The Flood Studies Report (FSR) provided the first unified framework for conducting flood frequency analysis at both gauged and ungauged catchments in the UK, and it has been instrumental in the continued development of flood frequency methodologies worldwide. The FSR procedure is based on the index-flood method, where a flood frequency curve is represented by the product of the following two elements.

- An index flood, defined as the mean annual maximum flood (QBAR).
- A dimensionless growth curve, derived through the fitting of a GEV distribution to normalised AMAX data within a specified geographical region.

The FSR divided the British Isles into eleven different regions and estimated a growth curve for each region as shown in Figure 1.1.



Region curves showing average distribution of $Q/\bar{Q}$ in each region.

Figure 1.1 Geographical regions and the associated growth curves for flood frequency analysis in the UK, as defined by the FSR (From Sutcliffe, 1978).

The individual growth curves were fitted to the regional data by manually adjusting the growth curve parameters. As well as growth curves, the FSR provided a set of regression models for predicting the index flood in each region. The regression models linked QBAR to a set of catchment characteristics which a user would need to obtain from both Ordnance Survey and FSR thematic maps. The catchment characteristics required were the following nine variables: AREA, MSL, S1085, STMFRQ, SOIL, LAKE, URBAN, SAAR and RSMD,

Subsequent research by Hosking *et al.* (1985) suggested that the algorithm used to derive a FSR growth curve for a given catchment did not perform as well as a new procedure which was still based on the GEV distribution, but which derived the growth curve by using probability-weighted moments (PWM), as described by Wallis (1981). Some researchers developed methods allowing the FSR approach to be used for dealing with flood frequency analysis in urban areas (Packman, 1980) while others placed an increased focus on the use of data transfer from gauged (donor) catchments to ungauged catchments as a possible method for enhancing estimates at the ungauged catchments (Institute of Hydrology, 1983).

1.1.3 Flood Estimation Handbook (FEH)

Rather than dissatisfaction with the performance of the FSR method, it was methodological developments in regional flood frequency analysis that led to a re-evaluation of the FSR methodology as presented in the FEH. In particular, two developments that have been influential both in the UK and elsewhere are the seminal work by Hosking and Wallis (1997), who popularised the L-moment approach to regional frequency analysis, and the introduction of the region of influence (ROI) approach by Burn (1990).

In the time that passed between the publication of the FSR and the onset of the FEH development, advances in digital mapping techniques, statistics and hydrological modelling combined with the widespread availability of desktop computing to make the development of new system for flood estimation possible. This was a more flexible but, at the same time, a more complex and computationally burdensome system than the FSR. While retaining the index-flood method as the basis of the procedure, the FSR method of dealing with the growth curve component using geographical regions was replaced in the FEH by the concept of pooling-groups. Here, for each site of interest, a unique ‘region’ (pooling-group) is created based on ‘hydrological similarity’. The pooling-group for a given site of interest was defined by searching a database of 1,000 potential sites to find catchments judged to be ‘hydrologically similar’. This judgement was based on similarity of catchment area (AREA), annual average rainfall (SAAR) and hydrological soil properties as defined by the HOST classes (BFIHOST). An example of a pooling-group is shown in Figure 1.2.

Figure 1.2 Example of a subject site (red cross) and the most hydrologically similar gauged catchments (black squares) included in the FEH pooling-group.

The use of fixed geographical regions had been criticised for pooling together data from catchments with very different sizes and soil types (Institute of Hydrology, 1999), as well as being counter-intuitive when a particular site of interest is located close to the border between two geographical regions. While the pooling approach addresses both these problems, it should be noted that there may be locations with catchment characteristics outside the normal range of values that might still be perceived as being lon a boundary (i.e. be adjacent to an empty region in catchment descriptor space). In comparison to using geographical space, such a boundary problem might not be as easily identified.

The FEH changed the index flood from the mean annual flood (QBAR) to the median annual flood (QMED), as the latter was considered to be more robust to outliers in short series. A single regression model linking the QMED to a set of six catchment descriptors was developed for general use in the UK. The resulting equation is often referred to as ‘the QMED equation’. Additional calculation steps were introduced with the aim of improving the estimates from the QMED equation by making use of information at gauged sites that were either geographically close or judged to be hydrologically similar to the target catchment (termed donor and analogue catchments, respectively).

The FEH also recommended that the Generalised Logistic (GLO) distribution, rather than the GEV distribution, should be adopted as default distribution in the UK.

A key advance in the FEH was the use of digitally derived catchment descriptors and the release of the accompanying FEH CD-ROM. The digital catchment descriptors replaced the catchment characteristics that previously had to be derived manually from maps.

1.1.4 Post-FEH

A comprehensive assessment of the FEH statistical method was reported by Morris (2003) based on results obtained by generalising the method to the entire river network in the UK. Many of the recommendations made by Morris to improve the FEH have been addressed in the work undertaken in this project.

More recently, a series of publications by Kjeldsen and Jones (2006, 2007, 2008) have identified the link between the model error structure of the QMED regression model and the benefit obtained from the use of data transfer from donor and analogue catchments. The results of these studies have informed the development of both the new QMED equation and the revised data transfer procedure presented in this study.

1.2 Why is an update needed?

While the FEH has served the hydrological community well, the additional ten years of peak flow data generated by the HiFlows-UK project (see Table 2.1) needs to be taken into account. In addition to the extended record lengths, the HiFlows-UK project put substantial effort into reconsidering the level-discharge rating curves, general quality control and assessing the reliability of the data-records. Given that the new database provides substantially longer records while enabling the avoidance of poor-quality data, an update of the FEH procedures was considered necessary.

This project also provides an opportunity to disseminate the result of research into flood frequency analysis, undertaken at the Centre for Ecology and Hydrology (CEH) since the publication of the FEH in late 1999.

1.3 Outcome of the present study

As outlined above, the present study has examined a number of aspects of the FEH methodology. Details of these analyses are given in later chapters. In order to provide an indication of the scope of this work, Table 1.1 provides a summary of the recommendations being made as a result of this project

Table 1.1 Recommendations from the present study.

Component of FEH methodology	Recommendations	Comments
QMED equation.	Equation using revised set of catchment descriptors.	• Fitted to updated data-set. • Improved representation of relation to catchment descriptors. • Outperforms the FEH equation.
Using gauged data to adjust initial estimate of QMED.	• Discontinue use of “analogue” (hydrologically similar) catchments. • Weight donor catchments using geographical distance.	• Adjustments based on FEH donor catchments likely to make estimates worse. • New donor scheme Improves estimates of QMED.
Pooling-groups: selection of similar catchments.	New set of catchment descriptors used to measure hydrological similarity.	Includes a new catchment descriptor for floodplain extent not available for FEH.
Pooling-groups: weighting within pooling-group.	• New weighting scheme making direct use of both a new measure of hydrological similarity and record lengths. • Explicit treatment of case where target catchment is gauged.	• New weights avoid pitfalls in FEH formulation as noted by users. • FEH used the same weights for both gauged and ungauged subject catchments. • Improved performance demonstrated.
Default distribution.	Retain GLO as default.	Assessment based on improved methodology and gave same conclusion as FEH.
Catchment descriptors.	• Digital data-sets for new descriptors constructed, most importantly for flood plains. • Possible usefulness of new descriptors assessed throughout procedures.	New flood plain descriptor contributes to revised pooling-group methodology.

1.4 Structure of the report

This report presents the results of the analysis undertaken as part of the current project.

Chapter 2 contains a summary of the data used in this study, both flood data and catchment descriptor data.

Chapter 3 details the development of a new range of catchment descriptors quantifying the extent of floodplains in the catchment.

Chapter 4 presents the development of a new QMED equation.

Chapter 5 introduces a new procedure for data transfer from gauged donor sites to an ungauged target site.

Chapter 6 presents the new procedure for forming pooling-groups and estimating the pooled growth curve.

Chapter 7 is concerned with finding a suitable distribution type for use as the default distribution in the UK.

Chapter 8 provides a short summary of the findings of this study and how the new procedure relates to the existing FEH statistical procedure.

Chapter 9 presents the general conclusions of the project and outlines some ideas as to how research into statistical methods for flood frequency estimation might be progressed in future.

Appendices A and B provide details of the data used for this study.

Appendices C and D provide mathematical details that were not appropriate in the main text.

2 Appraisal and selection of data

The development of statistical models for flood frequency analysis requires two types of data: i) observed flood peak data, and ii) data on physical catchment descriptors. The following sections describe the data that have been collected and analysed in this study. This study also developed a new set of catchment descriptors measuring the extent of floodplains and washlands in catchments. The details of how these descriptors were derived are reported in Chapter 3.

2.1 Flood peak data

Two types of flood peak data have traditionally been used in statistical flood frequency analysis: annual maximum (AMAX) series and peaks-over-threshold (POT) series of instantaneous flow. AMAX series consist of the largest value observed within each water-year, whereas POT series consist of the peak flow of all independent peaks exceeding a specified threshold. A comprehensive review of how to extract these flow series was provided as part of the FEH (see Vol.3, Chapter 23) and is not repeated here. Both the AMAX and POT series used in this study were obtained from the HiFlows-UK project. The final water-year in the flow series available for the present project is 2002 (October 2002 to September 2003).

2.1.1 Annual maximum series

The HiFlows-UK database contains AMAX series from 962 gauging stations located throughout the UK. Initial screening of the data, combined with further amendments received from the HiFlows-UK team, and liaison with scientific staff at the National River Flow Archive (NRFA) introduced a number of corrections to the initial data set. Further adjustments were made based on anomalies identified as part of the subsequent modelling of the data.

A total of 112 records were found to be unsuitable for use in this project. The majority of these records had already been identified by the HiFlows-UK team as unsuitable for estimation of QMED and unsuitable for inclusion in a pooled analysis. A further 42 gauges were discarded as no suitable set of catchment descriptors could be identified. (Note that similar cases arose in the FEH study.) These exceptional cases relate to catchments where the catchment-areas calculated from the present version of digital map information have an unacceptable disagreement with the areas generally accepted for those catchments. Finally, 206 gauges were omitted from the analysis as the degree of urbanisation on these catchments was sufficiently high ($URBEXT_{2000} > 0.030$) for them to be considered non-rural. For a more in-depth discussion of the revised definition of an urban catchment using $URBEXT_{2000}$ compared to that used in FEH, please refer to Bayliss *et al.* (2006).

The following paragraphs summarise some quantitative differences between the updated data set and that used in the FEH. As well as these differences, one should recall that the HiFlows-UK project attempted a coordinated quality-control assessment of the data, including an assessment of the rating curves. There is therefore an expectation that the dataset analysed here will be of a higher reliability than that available for the FEH.

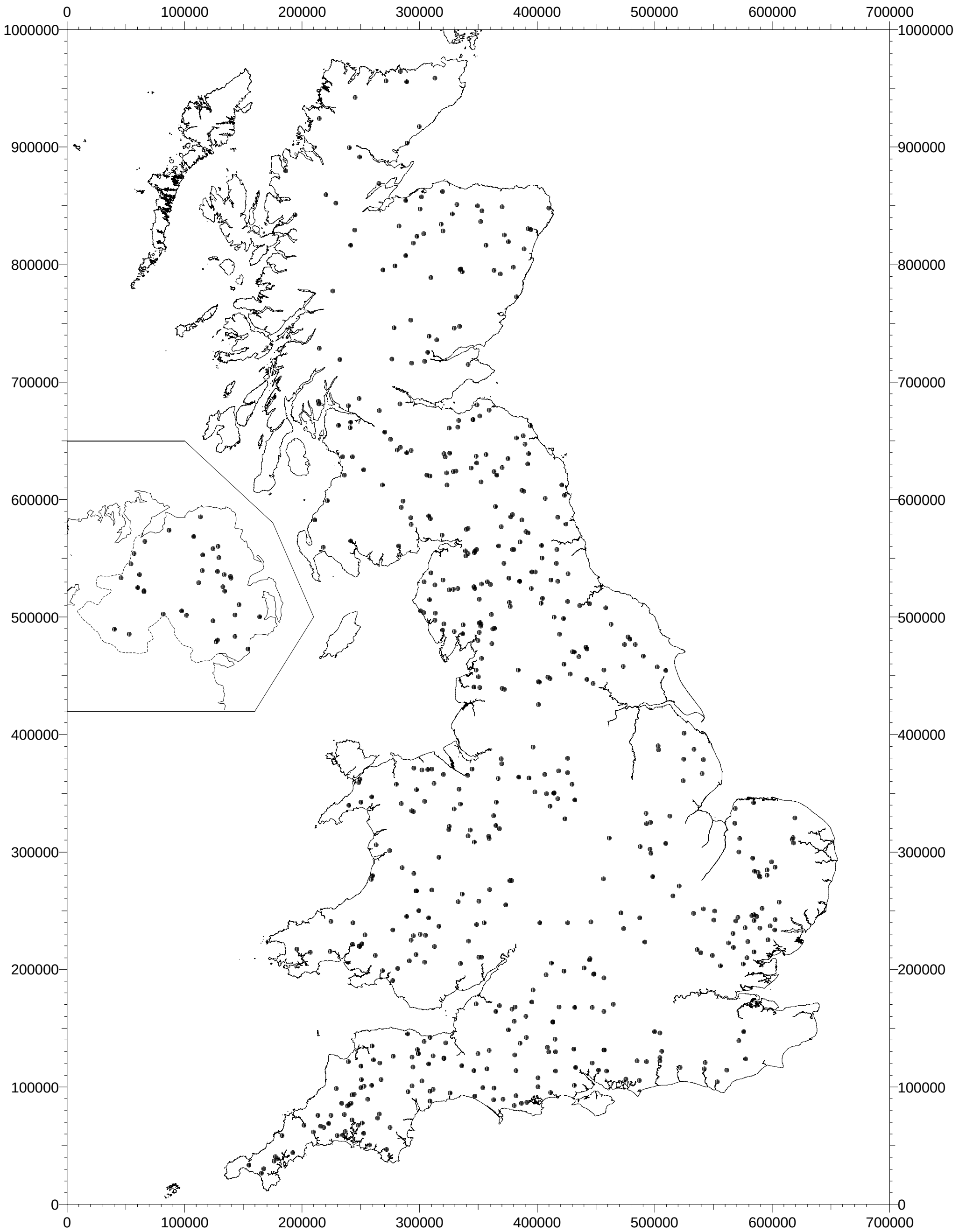


Figure 2.1 Location of 602 gauging stations on rural catchments providing instantaneous annual maximum flood peak data.

The final data set consisted of 602 rural catchments. The locations of the gauging stations are shown in Figure 2.1. Appendix A provides details of these 602 catchments. A summary of the data-set is shown in Table 2.1. The statistical methodology established in the FEH project was based on a total of 728 rural catchments, 126 more than used in this study.

Table 2.1 Summary of AMAX data sets [no. of years of data]

	HiFlows-UK	FEH
Number of gauges	602	728
Shortest record length	4	2
Longest record length	117	84
Mean record length	32.7	22.7
Number of AMAX events	19679	16528

From the comparison of the two data sets in Table 2.1 it is clear that, even though the FEH used more gauging stations, the total number of AMAX events is higher in the HiFlows-UK data set. Note that for records shorter than 14 years, the FEH used POT data to derive QMED, and only records with more than seven years were included in the pooled analysis. In fact, a total of only 698 sites were used in the FEH for the pooled analysis. A further comparison of the two data sets is shown in Figure 2.2 in the form of histograms of record length.

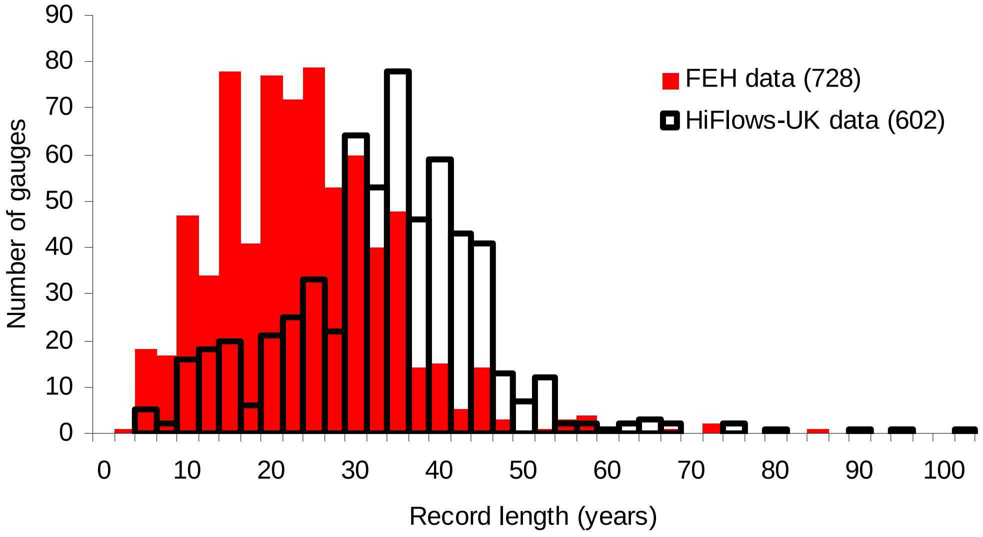


Figure 2.2 Histograms comparing record length of FEH and HiFlows-UK data sets.

Again, the histograms in Figure 2.2 illustrate the effect of including the additional AMAX data from the end of the FEH data (at best mid-1990s) to end of water-year 2002 (which represents October 2002 to September 2003). This increase in record length will generally reduce the sampling uncertainties of the estimates of QMED and of the L-moment ratios.

2.1.2 Peaks-over-threshold series

The FEH advocates the use of POT data for estimation of QMED where the AMAX record available is short, where short is defined as less than 14 years of AMAX data. Unfortunately, the quality of the POT series available in the HiFlows-UK database at the time of this project was found to be inadequate. In particular, the recorded information concerning start and end dates was generally poor, as was the recording of periods of missing data. The decision was therefore made not to use POT data in this project. Because of the relatively long data series in HiFlows-UK, only a relatively small percentage of stations were affected by this decision.

2.2 Catchment descriptors

The digital catchment descriptors used in this study were mainly extracted from the FEH CD-ROM Version 2 (CEH, 2007) for each of the 602 gauged catchments. The number of catchment descriptors potentially available is large, but only a subset of variables previously found to be useful in flood studies were included in this study. In addition to the existing descriptors available from the FEH CD-ROM, a series of additional descriptors were developed for this project. These are as follows.

- The extent of floodplains (FPEXT, FPBAR, FPLOC).
- The steepness of design rainfall growth curves (PRAT).
- The annual evaporation (EVAP).

The last two were easily derived from data-sets already available, while the floodplain descriptors required more work. A comprehensive description of the floodplain descriptors is the focus of the next chapter, while the other two descriptors are described in this Section (2.2.2-3). It should be noted that the SPRHOST descriptor is not included in the final set of descriptors used for this study (Table 2.2). Instead, BFIHOST is used as a measure of hydrological soil properties. The BFIHOST descriptor is considered more reliable (Kjeldsen *et al.*, 2005) as it is derived from a significantly larger data set than SPRHOST. When SPRHOST was considered as a candidate variable for modelling purposes, it provided no extra benefit once use had been made of BFIHOST.

Table 2.2 Summary of catchment descriptors used in this study

Descriptor name	Unit	Range	Note
AREA	km^2	[0;∞[	Catchment area as defined by DTM.
SAAR	mm	[0;∞[	Standard annual average rainfall 1961-1990.
FARL		[0;1]	Index of flood attenuation due to reservoirs and lakes.
BFIHOST		[0;1]	Baseflow index derived from HOST data.
PROPWET		[0;1]	Proportion of time when soil moisture deficit ≤ 6 mm during 1961-90, defined using MORECS.
DPSBAR	$m.km^{-1}$	[0;∞[	Mean catchment slope.
FPEXT		[0;1]	Floodplain extent.
PRAT		[0;∞[	Ratio between P_{100} and P_2 for 1-day rainfall (FEH DDF model).
RMED(1day)	mm	[0;∞[	Median annual maximum 1-day rainfall (derived using FEH DDF model).
EVAP	mm	[0;∞[	Average annual potential evaporation.

A summary of the catchment descriptors for the 602 catchments is given in Table 2.2. Note that the values used in the FEH project were directly equivalent to those included in Version 1 of the FEH CD-ROM and are therefore likely be less reliable than the values used in this study. Relevant improvements to the data in the upgrade from

Version 1 to 2 will have been derived from improved catchment boundary and drainage path definitions: these form the basis of all the catchment descriptors.

All variables were screened by plotting against QMED (all in log-space) to check for outliers, non-linear relationships and for possible cross-correlation between the descriptors. Figure 2.3 shows a matrix of scatter plots of the catchment descriptors and it also includes the cross-correlations between the descriptors. Figure 2.4 is intended as a guide to the interpretation of Figure 2.3.

2.2.1 Adjustment of FARL values

The FARL values available from the FEH CD-ROM Version 2 relate to a fixed time-point determined by the reservoirs and lakes present in the underlying data set, which represents the current catchment configuration. However, some flood peak data may have been gauged during a period prior to the construction of a particular reservoir. It has therefore been necessary to adjust the initial FARL values to a set of values that represents the actual FARL values experienced during the period of recording. In some cases where the AMAX record spans a period from before and after the construction of a reservoir, part of the record was removed to obtain an AMAX record associated with a representative FARL value.

2.2.2 Steepness of design rainfall growth curves

The ratio between the 100-year and the 2-year rainfall (PRAT) is used in this project as a measure of the steepness of the design rainfall growth curve. Values have been calculated for each catchment under consideration using the FEH DDF model for rainfall frequencies. From Equations (2.2) to (2.4) in FEH Vol.2 (Faulkner, 1999), it is possible to derive the ratio between the 100- and 2-year design rainfall depths (for any duration) as

$$\text{PRAT} = \frac{P_{100}}{P_2} = \exp\left[C\left(y_{100} - y_2\right)\ln\left(D\right) + E\left(y_{100} - y_2\right)\right]. \tag{2.1}$$

Here P_T is rainfall depth for return period T, D is rainfall duration, y_T is the Gumbel reduced variate and both C and E are catchment average FEH DDF model parameters. In his appraisal of the FEH statistical method, Morris (2003, see page 113, line 5-7) stressed that any catchment descriptor reflecting the rainfall growth factors should reflect the relationship between the duration of flood-producing rainfall and catchment size. To allow for this, the descriptor PRAT was calculated based on 24-hour rainfall.

2.2.3 Annual evaporation

The opportunity to explore the value of potential evaporation (PE) as an explanatory value arose from the availability of a grid of PE values at CEH. This is based on a preliminary map of annual average total PE for short grass produced by the Met Office for previous studies. While evaporation might be used as a ‘stand alone’ variable, there is also the possibility that it might be useful in combination with SAAR so as to create a crude measure of “surplus rainfall”. Catchment-average values of PE have been derived for the catchments in the calibration data set. Evaporation was not considered as part of the FEH, but it has been found to be a useful predictor in a regression model linking QMED to catchment descriptors in south-east Australia (Rijal and Rahman, 2005).

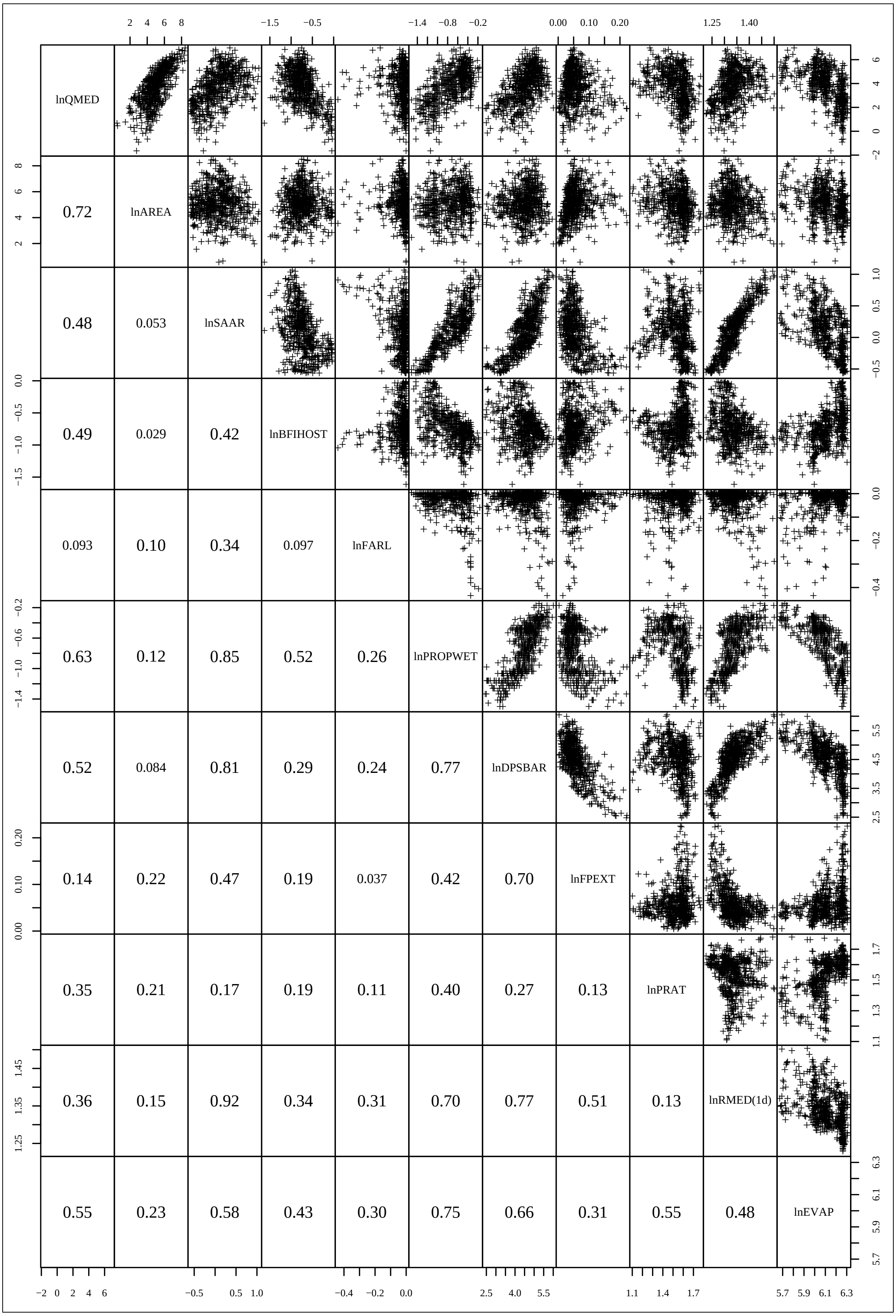


Figure 2.3 A matrix of scatterplots showing the relationship between pairs of catchments descriptors and QMED (log-transformed). Numbers below the diagonal indicate the correlation of the pairs shown as scatter plots above the diagonal.

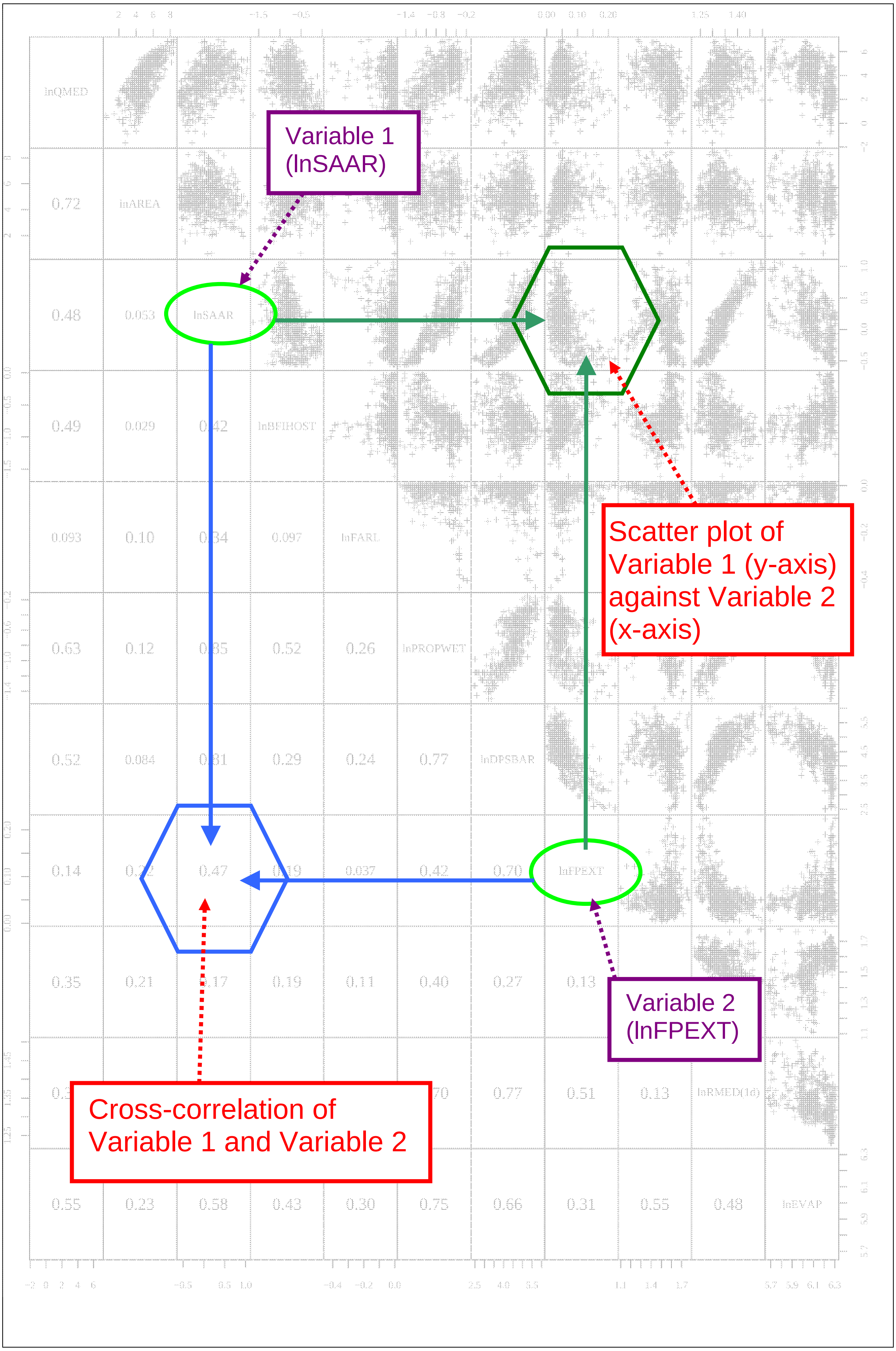


Figure 2.4 A guide to the interpretation of Figure 2.3.

3 Floodplain descriptors

Catchment floodplains and washlands provide temporary storage for flood water which, when flood levels are sufficiently high and inundation of these areas occurs, often affects the flood hydrograph by both reducing and delaying the peak flow. An examination of the flood growth curve for such catchments will typically show a flattening of the curve above the threshold flow at which inundation begins.

During the FEH research programme, a catchment descriptor was developed to index flood attenuation resulting from reservoirs and lakes (FARL). Although the importance of floodplains was recognised and noted in the FEH, a descriptor quantifying their effect was not defined. The current project seeks to re-examine the use of catchment descriptors to improve both the estimation of the median annual maximum flood (QMED) and the pooling of data to form estimates of the growth curve. Since catchment descriptors are pivotal in both these procedures, the present commission has provided an opportunity to develop an index, or indices, describing floodplains, to derive catchment values, and to test the usefulness of these values in subsequent analyses.

3.1 Choice of data

The choice of data on which to base indices describing floodplains was influenced by the need for the data to be:

- In digital format.
- At an appropriate resolution.
- Compatible with the DTM used to define other FEH catchment descriptors.
- Of good quality.
- Available for all parts of the UK.
- Accessible without delay.

Institute of Hydrology Report No. 130 (IH130) (Morris and Flavin, 1996) describes how flood depth data for a 100-year return period were derived in order to produce a flood risk map of England and Wales. The data fulfil the requirements listed above since they are:

- Available in digital format.
- Stored at a horizontal resolution of 50m and a vertical resolution of 0.1m. The original data described in IH130 were only provided where the catchment area exceeded 10km^2, as computation of values at every point (approximately three million in England and Wales) was judged to be impractical given the computer processing power available at that time. Consequently, in order for the data to be suitable for deriving catchment values in this study, where the required points can have a drainage area as small as 0.5km^2, flood depth values were derived for all nodes where the catchment area exceeded 0.2km^2 (again chosen to avoid unnecessary computation since few floodplains are located close to the watershed).

- Derived using the DTM developed at CEH Wallingford. Additionally, since the FEH catchment descriptors used in this study were redefined using improved digitised river data and the latest version of the DTM, the flood depth data were also redefined to the same standard.
- Consistent with independent map sources and therefore judged to be of good quality. The IH130 flood depth data were produced by generalised procedures based on catchment characteristics in order that data could be generated for all locations. Accordingly it should be recognised that the data represent estimates of flood depth. However, Morris and Flavin (1996) report how comparisons with Section 24 mapping indicated that there was good agreement between mapped and modelled flood extent.
- Provided for the whole of the UK. Data were originally defined for England and Wales only, but subsequently also derived for Northern Ireland and the Scottish mainland. The more recent extension of the CEH DTM to include Scottish islands meant that UK-wide coverage of flood depth data was achieved.
- Stored at CEH Wallingford and, therefore, available for immediate use within the project. The data are free for use in the development of floodplain indices as part of the research programme.

3.2 Revision of IH130 flood depth data

The IH130 methodology defines floodplains as those points where the depth is greater than zero based on the estimated 100-year flood level. The procedures do not exclude parts of the catchment occupied by lakes and reservoirs, and consequently flood depth values are stored at these locations if they are estimated to have been inundated by the 100-year flood.

The attenuation of floods by on-line reservoirs and lakes is described numerically by the FARL index. The computation of FARL index values excludes those reservoirs and lakes that are off-line as they typically have, as water bodies, a minor role in attenuating floods. Since floodplain indices are likely to be used alongside the FARL index in the research programme, and potentially in new procedures, it is important that they compliment each other and avoid any ‘double counting’ of areas of the catchment likely to contribute to flood attenuation. Since FARL already takes account of the attenuation effect of on-line reservoirs and lakes, flood depth values attributed to these areas should be excluded from the computation of floodplain index values. Conversely, values assigned to areas of off-line reservoirs and lakes that lie within the floodplain, need to be included in the computation of floodplain index values since they are ignored in the derivation of the FARL values.

In order for flood depth values assigned to areas of on-line lakes and reservoirs to be excluded from the computation of floodplain indices, and those values attributed to areas of off-line water bodies to be included, a revised grid of flood depth values was produced. Firstly, a 50m square grid of flags was derived, indicating the on-line/off-line status of all lakes and reservoirs. Secondly, this grid was combined with flood depth values so that the resultant dataset excluded flood depth values assigned to areas of on-line lakes and reservoirs.

3.3 Key characteristics

If the indices developed to describe the attenuation effect from floodplains are to be successful in contributing to the FEH procedures, it is important that they describe the characteristics of floodplains that often result in reduced and delayed flood peaks. The extent to which a floodplain influences downstream flood flows will often depend on relatively subtle changes in riparian elevation. However, given the understandable approximations of the IH 130 methodology and the relatively coarse resolution of both the underlying data and resultant flood depth values, descriptors based on these values can only describe floodplain characteristics in a generalised way. Nevertheless, the flood depth data-set is able to provide information on three key characteristics of floodplains; extent, storage capability and location in the catchment.

3.4 Definition of the descriptors

The FARL index describes the catchment’s capability to attenuate floods by evaluating the extent and location of each lake and reservoir in the catchment. Consequently, the initial thought was to adopt the principles applied in the derivation of FARL values to calculate a floodplain index. However, the representations of water bodies and floodplains in the available datasets had significant differences to those of the IH130 scheme. Lakes and reservoirs are recorded as discrete entities with, in the vast majority of cases, a single defined outlet for each water body. Conversely, floodplains defined by the IH130 procedures are often narrow features that follow the river, sometimes connecting wider areas, but typically with no clear single end point or ‘outlet’ to the floodplain within the defined catchment. This is a crucial difference since the computation of the FARL index relies on finding a single outlet for each lake and reservoir. Accordingly, the proposal to adopt the principles employed to define FARL values in the derivation of floodplain index values was rejected.

Since it was impractical to follow the procedures used to define FARL values, derivation software was written to describe floodplain extent and location independently. Additionally, since depth values were available, an index of floodplain storage could also be defined.

3.4.1 Floodplain extent (FPEXT)

Floodplain extent is defined as the fraction of the catchment that is estimated to be inundated by a 100-year flood. Index values are calculated by summing the number of 50m x 50m squares in the catchment where the assigned 100-year flood depth is greater than zero (use of the revised flood depth data means that any nodes located within on-line lakes or reservoirs are ignored (see Section 3.2)). The total area of floodplain in the catchment is divided by the drainage area to give an index value between 0 and 1.

3.4.2 Floodplain location (FPLOC)

The location of floodplains within the catchment is described using the same principles employed to derive values of the FEH index URBLOC (see the glossary). In this evaluation, the position of urban and suburban areas relative to the catchment outlet is calculated (Bayliss, 1999). In the case of URBLOC, a composite index was defined with a different weighting applied to the proportion of the catchment subject to suburban development compared to that defined as urban. Compared to this, the computation of floodplain location (FPLOC) is more straightforward, since only one variable (flood depth) is involved. Firstly, “floodplain nodes” are defined as those nodes assigned a flood depth greater than zero. Then, following the procedures employed to define URBLOC, the distance along the DTM-derived drainage path from each floodplain node to the catchment outlet is calculated. The mean of these distances from floodplain nodes is then divided by the mean distance from all nodes to the catchment outlet. FPLOC is not defined when there are no floodplains in the catchment, and poorly defined when only very small areas of floodplain are present. Therefore, when FPEXT is less than 0.005, FPLOC is not calculated.

3.4.3 Mean flood depth (FPDBAR)

The IH130 flood depth dataset not only provides an estimate of the extent of the 100-year floodplain, but also supplies, for each node, an estimate of the flood depth (i.e. flood level minus elevation). This provided an opportunity to estimate the volume of water stored on catchment floodplains for a 100-year event rather than just its extent, and therefore an opportunity to characterise the attenuation effect on flood flows more accurately.

The first stage in the computation of FPDBAR is to estimate the total storage on catchment floodplains based on the sum of the flood depth recorded at each 50m x 50m square. The second stage in the calculation is the standardisation of the sum of flood depth values. Without standardisation the sum would increase as the catchment area increased, and AREA is a descriptor in its own right. In order that index values can be compared for catchments of any size, the sum of the flood depths was divided by area. Consequently, to characterise the effect of the floodplain(s) on the whole catchment, the sum of the flood depths was divided by the catchment area (which can be thought of as the mean flood depth (in cm) over the entire catchment).

3.5 Deriving descriptor values

Catchment descriptor values used in the research programme have been derived using the latest version of the CEH DTM (i.e. that used to derive values presented on Version 2.0 of the FEH CD-ROM). Accordingly, the same DTM was used to define catchment boundaries and drainage paths in the derivation of values for the new descriptors FPEXT, FPLOC and FPDBAR. Values were derived for the whole of the UK, including the Isle of Man. The data were stored in compressed format in Oracle tables. The completeness and integrity of the data were checked by mapping values at 1:250,000 scale and in comparison with flood depth maps.

3.6 The FPEXT, FPLOC and FPDBAR data

Values for 920 of the 962 HiFlows-UK catchments were retrieved from the compressed format tables and stored in a standard format table for use in the study. Descriptor values for the other 42 catchments were not used as they were either smaller than 0.5 km^2 or the DTM-derived drainage area differed by more than a factor of 1.1 from the published area. Appendix B presents a table giving values of FPEXT, FPLOC and FPDBAR for the smaller set of catchments consisting of the 602 non-urban catchments used in this study. This matches the table in Appendix A, which shows gauge details together with values for QMED and information about the highest flow in the data-record.

3.6.1 FPEXT

Figure 3.1 indicates that the 100-year floodplain is a relatively minor feature for the majority of these catchments. However, for a significant proportion (19 per cent) the floodplain occupies more than 10 per cent of the catchment, and for 17 sites represents more than 20 per cent of the catchment.

Of the 602 non-urban catchments, the largest values of FPEXT occur for Arley Brook at Gore Farm (Gauge No. 68011, AREA=33.76 km^2, FPEXT=0.2498) and the River Ancholme at Bishopbridge (Gauge No. 29004, AREA=59.03 km^2, FPEXT=0.2478). The lowest values of FPEXT occur for the River Yeo at Parkham (Gauge No. 50801, AREA=7.51 km^2,FPEXT=0.0023) and Horner Water at West Luccombe (Gauge No. 51002, AREA=20.38 km^2,FPEXT=0.0028).

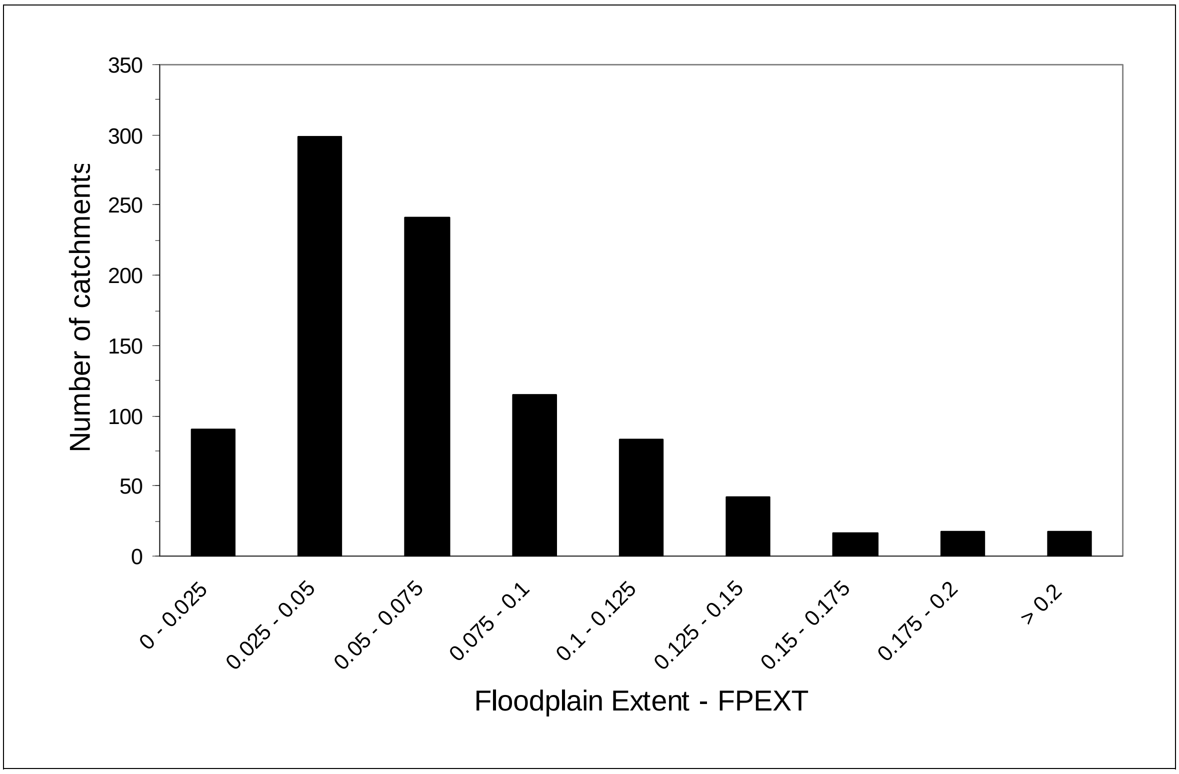


Figure 3.1 Numerical distribution of FPEXT values

3.6.2 FPLOC

FPLOC has been calculated for 915 HiFlows-UK catchments where floodplain extent (FPEXT) is greater than 0.005 (0.5 per cent) of the catchment. The index describes the mean distance along drainage paths from floodplain areas to the catchment outlet, relative to the mean from all points in the catchment. Since the mean distance is generally a point half-way between the catchment outlet and the most distant watershed, a floodplain close to the gauged point will give FPLOC values close to zero. At the opposite extreme, a floodplain in the most distant part of the catchment will give a value approaching two. Figure 3.2 confirms what one might expect; that floodplains are generally found in the lower part of the catchment.

Of the 602 non-urban catchments for which FPLOC has been defined (598 catchments), the largest values of FPLOC occur for Burbage Brook at Burbage (Gauge No. 28070, AREA=8.45 km^2, FPLOC=1.242, FPEXT=0.0310) and the River Witham at

Saltersford (total) (Gauge No. 3005, AREA=123.5 km^2, FPLOC=1.203, FPEXT=0.0925). The lowest values of FPLOC occur for Costa Beck at Gatehouses (Gauge No. 27038, AREA=7.98 km^2, FPLOC=0.383, FPEXT=0.1253) and Foston Beck at Foston Mill (Gauge No. 26003, AREA=59.4 km^2, FPLOC=0.409, FPEXT=0.1057).

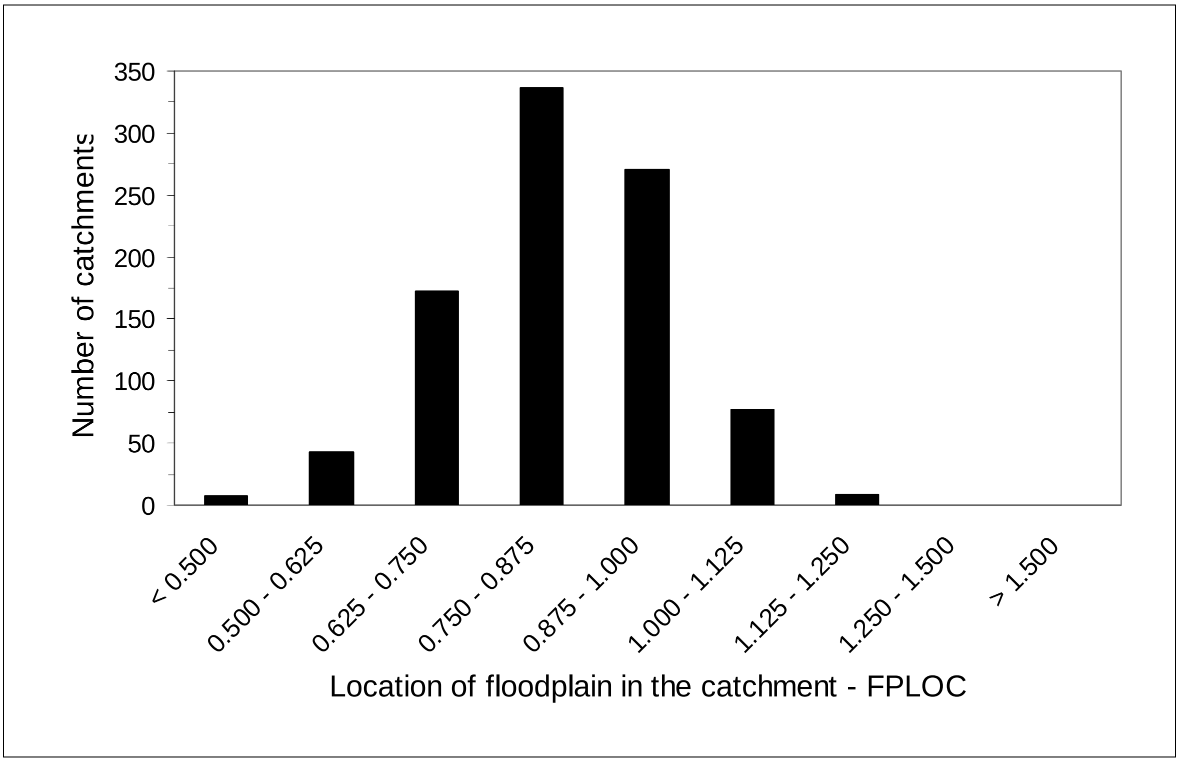


Figure 3.2 Numerical distribution of FPLOC values

3.6.3 FPDBAR

Although FPDBAR values are given as a flood depth in centimetres over the catchment, the absolute amounts themselves are unimportant. Since the storage on the catchment floodplains is already standardised by dividing by the catchment area, it is the relative differences between FPDBAR values that indicate the importance of floodplains on one catchment compared to another. The numerical distribution of FPDBAR values (Figure 3.3) is similar to that of FPEXT values (Figure 3.1) – both are positively skewed. Indeed, Figure 3.4 shows that the two descriptors show some correlation ($r^2 = 0.52$) and intuitively this would seem to be correct. Typically the estimated depth of floodwater on the floodplain for the 100-year event will be within a relatively limited range. In general, only on those catchments where there is significant floodplain extent and therefore appreciable flood storage, will there be correspondingly high values of FPDBAR.

Of the 602 non-urban catchments, the largest values of FPDBAR occur for the Ribble at Arnford (Gauge No. 71011, AREA=203.22 km^2, FPDBAR=3.793 cm, FPEXT=0.0987) and the Ribble at Henthorn (Gauge No. 71006, AREA=446.28 km^2, FPDBAR=2.348 cm, FPEXT=0.0925). The lowest values of FPDBAR occur for the River Yeo at Parkham (Gauge No. 50801, AREA=7.51 km^2,FDBBAR=0.023 cm, FPEXT=0.0023) and Horner Water at West Luccombe (Gauge No. 51002, AREA=20.38 km^2,FDBBAR=0.038 cm, FPEXT=0.0028): these are also the two catchments with the lowest values of FPEXT.

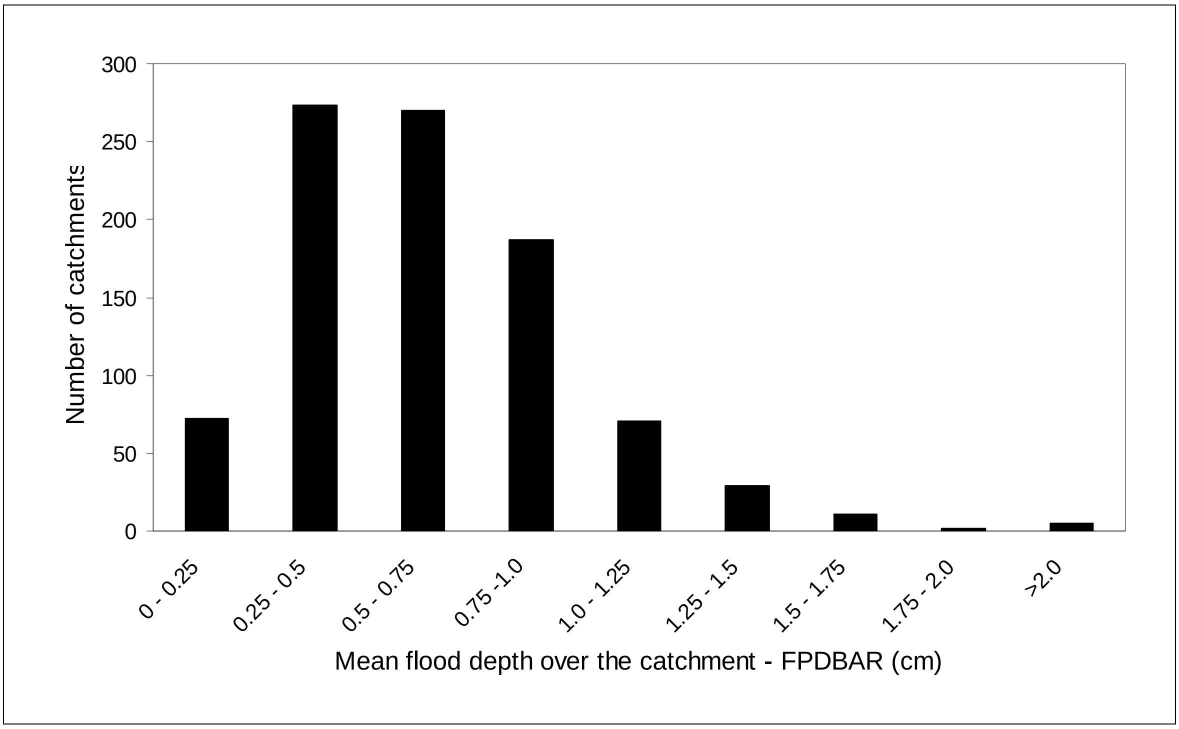


Figure 3.3 Numerical distribution of FPDBAR values

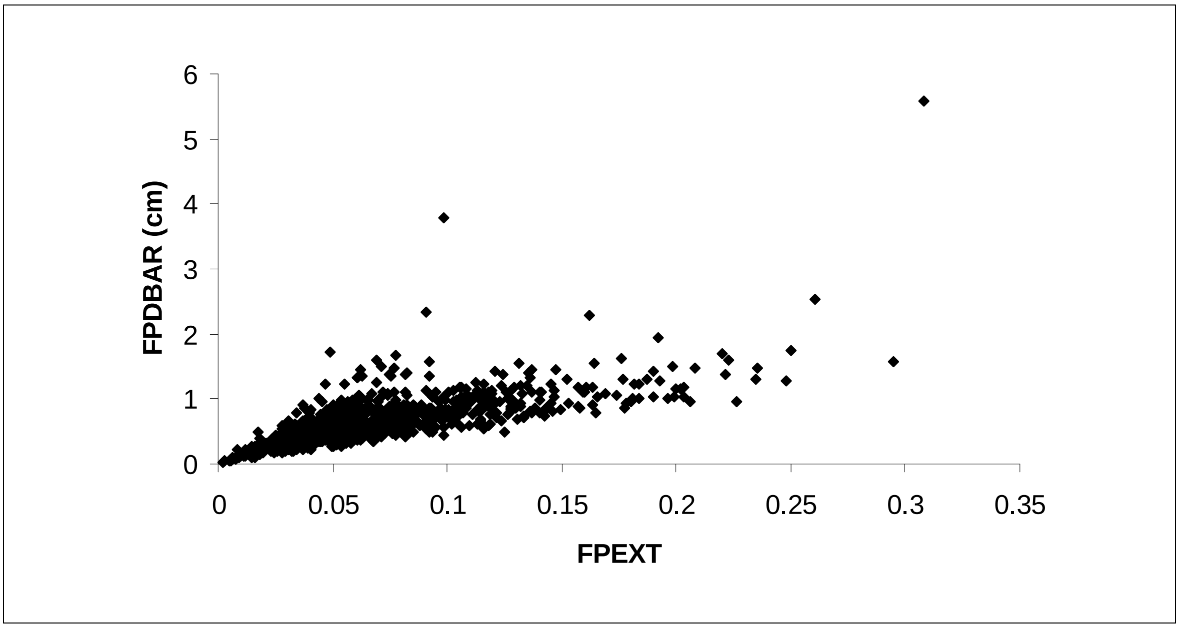


Figure 3.4 Relationship between FPDBAR and FPEXT values

4 Improving QMED estimation

The use of regression models to forge links between an index flood parameter (QBAR or QMED) and a set of lumped catchment descriptors is a long-established practice in engineering hydrology, both in the UK and elsewhere. This is partly due to the simple nature of the regression models, and partly due to the relatively limited data requirements when compared to more detailed hydrological models.

The selection of catchment descriptors to be included in a revised QMED equation is a complex task and requires a balance to be struck between the following tasks.

- Obtaining the best possible fit to the data using a reasonable number of descriptors.
- Ensuring a reasonable hydrological interpretation of the final model.

As described in the FEH, the final choice has evolved as part of an iterative procedure where models were tested, residuals investigated and, as a result, new models developed. Unlike both the FSR and the FEH, the present study does not start with a 'blank canvas'. A comprehensive data analysis was undertaken as part of the FEH to investigate the optimal regression model for linking the QMED to the digital catchment descriptors, and the work undertaken in this project does build on the findings of the FEH to some extent. In fact, initial investigations suggested that a regression model using the same catchment descriptors used in the FEH QMED model, but fitted to the HiFlows-UK data, performed relatively well.

The next section presents a review of similar models that have been published previously for use in the UK (Section 4.1). The later sections (4.2 to 4.6) are concerned with various aspects of the development of the statistical model underlying the QMED equation.

4.1 Review of previous models (QBAR and QMED)

This section is a review of the models and results obtained in previous studies linking an index flood (QBAR or QMED) to catchment characteristics or descriptors in the UK. The review is organised so that a general summary of previous studies is followed by a more in-depth discussion of the QMED equation developed as part of the FEH (Institute of Hydrology, 1999). More emphasis is given to the latter, as this study is an extension of the work undertaken in the FEH. Specifically, they both use QMED as the index flood and they use digital catchment descriptors rather than the FSR catchment characteristics (catchment descriptors in FSR terminology) that had to be obtained manually from thematic and 1:25000 OS maps.

In a separate study Dawson *et al.* (2006) attempted to link QMED to the FEH catchment descriptors using artificial neural networks (ANN). The results seemed to indicate that the performance of the ANN models were comparable to the regression models developed in the FEH.

4.1.1 Pre-FEH models

A summary of regression models from the literature relating to UK-based studies is shown in Table 4.1. These models link QBAR or QMED to either catchment characteristics or catchment descriptors.

Table 4.1 Regression models previously used in the UK for linking the index flood to catchment descriptors

Source	Index flood	Descriptor source	Equation	r^2	fse	N*
Cole (1965)	QBAR	OS maps	$QBAR = C \times AREA^{0.85}$			56
Nash & Shaw (1965)	QBAR	OS maps	$QBAR = 0.76 AREA^{0.74}$	0.60	1.499	57
Nash & Shaw (1965)	QBAR	OS and thematic maps	$QBAR = 9.65 \times 10^{-8} AREA^{0.85} SAAR^{2.2}$	0.92	1.196	57
FSR (NERC, 1975) developed an equation for each different hydrometric region#	QBAR	OS and thematic maps	[$] $QBAR = 0.0201 AREA^{0.94} STMFRQ^{0.27} S1085^{0.16} SOIL^{1.23} RSMD^{1.03} (1 + LAKE)^{-0.85}$	0.911	1.472	532
FEH (IH, 1999)	QMED	Digital data on FEH CD-ROM	$QMED = 1.172 AREA^{AE} \left(\frac{SAAR}{1000}\right)^{1.560} FARL^{2.642} \left(\frac{SPRHOST}{100}\right)^{1.211} 0.0198^{RESHOST}$	0.916	1.549	728

Notes: [*] N = number of catchments

[#] Equations with different intercepts were developed for different regions

[$] Example shown gives the average intercept. A different three-variable equation was provided for Essex, Lee and Thames catchments

It is interesting to observe the apparent similarities between the models listed in Table 4.1, especially the similarity of the coefficients of the AREA term. Note that the FEH model was fitted under constraints as the combination of the ln[AREA] and ln[AREA]^2 terms could lead to unrealistic behaviour for certain parameter values.

4.1.2 The QMED equation in the Flood Estimation Handbook

Chapter 13 in Volume 3 of the Flood Estimation Handbook (Institute of Hydrology, 1999) describes how the final selection of catchment descriptors to be included in the FEH QMED equation was based on the results from three main investigations.

- A comprehensive search over all possible combinations.
- The use of additional artificial variables to indicate the upper limit of the number of descriptors to include.
- In-depth investigations of partial residuals plots of selected candidate models.

The comprehensive search procedure was based on identifying the models with the highest r^2 values using from one to nine different catchment descriptors. Starting with a one-variable equation, the r^2 value was found to increase significantly as new descriptors were added. However, the improvement was more modest when using six to seven variables and with only marginal increases observed when using more than seven variables. In addition, models using more than seven variables were found to be hydrologically unacceptable (did not reflect the prevailing understanding of the flood generating mechanisms) and sensitive to which sites were excluded.

By including a number of randomly generated variables among the catchment descriptors, it was possible to identify the upper level of model complexity in terms of number of descriptors included in the model. It was found that the third best model (in terms of r^2) based on seven variables included a random variable. This, in combination with the behaviour described above, led to the largest number of variables allowed in the final QMED model being set at six.

Finally, inspection of the partial residual plots derived from a model containing five variables (ln[AREA], ln[SAAR], ln[FARL], ln[SPRHOST] and RESHOST) suggested that a term (ln[AREA])^2 should be included in the model because of a perceived non-linear effect due to catchment size.

4.2 QMED estimation at gauged sites

The FEH methodology described methods for estimating QMED from gauged records based on both annual maximum (AMAX) and peaks-over threshold (POT) series. It was recommended that POT data should be used where less than 14 years of AMAX data are available. However, as the quality of the POT series in the HiFlows-UK data base has been found to be inadequate for the current project, the estimation of QMED is based solely on AMAX series, regardless of record length. For the purpose of developing the QMED equation this is not considered problematic. In the regression model, each gauged site will be given a weight based on its sampling uncertainty, which means that sites with a short record length will be given little weight in the analysis.

4.2.1 Calculation of the median annual flood

Estimation of the QMED values based on annual maximum series is very straightforward. The median is the middle-ranking value in an ordered sample with n observations ($Q_{[1]} \geq \ldots \geq Q_{[n]}$) and is given as

$$QMED = \begin{cases} Q_{[m]} & \text{where } m = (n+1)/2, \text{for } n \text{ odd} \\ \left(Q_{[m]} + Q_{[m+1]}\right)/2 & \text{where } m = n/2, \text{for } n \text{ even} \end{cases} . \quad (4.1)$$

4.2.2 Uncertainty in QMED

As part of the FEH studies, the sampling uncertainty of QMED estimates obtained from both AMAX and POT data were obtained using a distribution-free resampling technique. The results were presented in FEH Vol.3 (Table 12.3) as a set of *fse* (factorial standard error) values depending only on record length. In the present study, the sampling uncertainty of the median is estimated based on asymptotic results assuming that the AMAX series originate from underlying GLO distributions. A general result allows the asymptotic sampling uncertainty of the median for any distribution to be estimated as

$$\sigma^2 \approx \frac{1}{4nf^2\left(F^{-1}(0.5)\right)} \quad (4.2)$$

where n is the record length, f is the probability density function of the distribution, F is the distribution function and F^{-1}(0.5) is the median quantile (0.5 point) of the distribution. Considering the logarithm of the median for a GLO distribution, equation (4.2) reduces to:

$$\sigma^2 \approx \frac{4\beta^2}{n} \quad (4.3)$$

where β is the scale parameter of the GLO distribution, as defined by the FEH Vol.3 (Section 15.3.2).

4.2.3 Adjusting QMED for climate variation

In the FEH a comprehensive analysis was conducted to assess the impact of climate variability and climate change on the flood hydrology of the UK, as observed using AMAX and POT data. No clear evidence of an impact due to climate change was identified, but there were indications of effects that were described as “climate variability”. A framework was developed for adjusting QMED values estimated from gauged records obtained over short periods. The rationale for a procedure adjusting for climatic variability is that values obtained using short records might reflect particular ‘flood rich’ or ‘flood poor’ periods and thus require adjustment to be representative of the true long-term QMED value. The FEH recommended that all records with less than 30 years of AMAX data be adjusted. The process described in FEH Vol. 3 (Chapter 20) for adjusting QMED according to climatic variability is rather complicated, and the results indicate a slight adjustment of values obtained for series less than 10 years long, but little systematic impact on longer series. Figure 4.1 compares the results obtained in the FEH Vol. 3 (Figure 20.2) with the corresponding results obtained in this study.

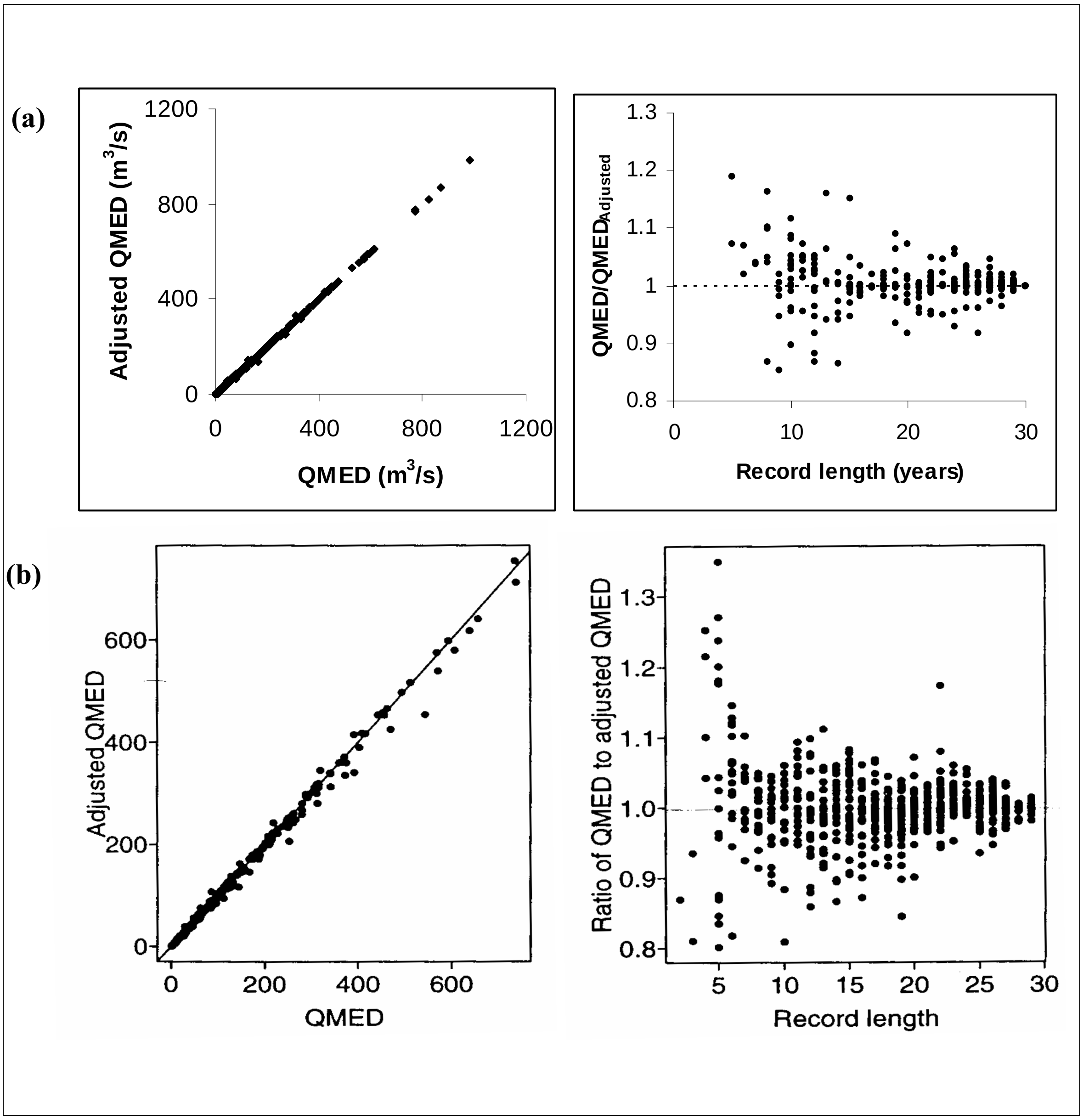


Figure 4.1 Results of climate adjustment on QMED for a) this study using HiFlows-UK, and b) FEH Vol. 3 (Figure 20.2). Figures compare estimates of QMED with the adjusted QMED values. The right hand graphs show the ratio of the two estimates plotted against record length.

The adjustment procedure is relatively complex since it relies on transfer of data from multiple other sites. This makes it difficult to estimate the sampling variance of the resulting adjusted QMED values, and this sampling variance plays an important part in the regression model (Section 4.3). In addition, the regression analysis needs the covariance of the sampling errors in the QMED values supplied for different sites. This is regarded as a significant problem given the reliance on estimates of variance and covariance of QMED to provide information on the weights assigned to each site in the regression analysis. In fact, if adjusted QMED values were required for other purposes, the preferred approach would be to derive these from the regression model presented here. In particular, the regression model would be supplied with unadjusted QMED values, and could be used to provide “optimal” adjusted QMED values for any and all catchments which would take account of both the information available via the relation to catchment descriptors and cross-correlation of the overall errors, which implicitly makes the adjustments for climatic variation included in the FEH study. The theory exists for doing this, but was outside the scope of the present study. However, because the full regression model does include all this structure, these implicit adjustments for climatic variation are included when constructing the regression-based estimates for ungauged catchments. The conclusion here is that, provided the regression model includes a good statistical description of the modelling errors, it is unnecessary to use additional models to pre-construct adjusted QMED values as was done for the FEH study.

The present study has not undertaken any major analysis to look for climate change effects, as distinct from climatic variation. The FEH study illustrated the difficulty of distinguishing between the two (FEH, Vol. 3, Chapter 20). However, part of the initial screening of the data (Section 2.1.1) involved examining time-series plots of the AMAX data looking for changes in the properties of the series. As for the FEH study, such changes could be associated with changes to the gauging structure, or to the catchment itself, rather than being obviously associated with climate change.

4.3 Regression model description

To relate the index flood variable from *n* different catchments to a set of catchment descriptors, consider a vector of sample (log transformed) median annual maximum floods, **y**, where individual sites are denoted with a subscript *i*. Each sample value is described in terms of a population regression model and two individual error components representing the sampling and modelling errors, ε_i and η_i respectively so that

$$y_i = \mathbf{x}_i^T \boldsymbol{\theta} + \eta_i + \varepsilon_i = \mathbf{x}_i^T \boldsymbol{\theta} + \omega_i \, , \qquad (4.4)$$

where $\boldsymbol{\theta}$ is a vector of regression model parameters and $\mathbf{x}_i$ is a vector of catchment descriptors with a value of one in the first location. Both errors are assumed normally distributed with zero mean values. The covariance of the sampling errors is denoted by $\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}$ and the corresponding covariance of the modelling errors is denoted by $\boldsymbol{\Sigma}_{\boldsymbol{\eta}}$, with the two errors assumed to be mutually independent. It is assumed that the elements along the diagonal of the modelling error covariance are identical and equal to σ_η^2. The covariance matrix of the vector of total errors, $\boldsymbol{\omega}$, is defined as

$$\boldsymbol{\Sigma}_{\boldsymbol{\omega}} = \boldsymbol{\Sigma}_{\boldsymbol{\eta}} + \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}} = \sigma_\eta^2 \left(\mathbf{R}_{\boldsymbol{\eta}} + \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}} \big/ \sigma_\eta^2 \right) = \sigma_\eta^2 \mathbf{G} \, , \qquad (4.5)$$

where $\mathbf{R}_{\boldsymbol{\eta}}$ is the modelling error correlation. The matrix **G** is introduced for computational convenience and is derived from values of σ_η^2 and $\mathbf{R}_{\boldsymbol{\eta}}$. In pioneering the use of the Generalised Least Square (GLS) procedure in hydrology, Stedinger and Tasker (1989) assumed the modelling covariance matrix to be of the form $\boldsymbol{\Sigma}_{\boldsymbol{\eta}} = \sigma_\eta^2 \mathbf{I}$, meaning that they assumed there to be no cross correlation between the modelling errors. In contrast, the model formulated here is more general and assumes the cross correlation to be represented by the associated modelling error correlation matrix $\mathbf{R}_{\boldsymbol{\eta}}$.

The sampling and model error components represent two distinctly different sources of error in the regression model. Start by assuming that a ‘true’ value of QMED could be estimated for each catchment if an infinite long series of AMAX data was available. In practice, QMED for a catchment has to be estimated from a finite series, which introduces a sampling error representing the difference between this sample estimate and the notional true value. The modelling error represents the inability of a particular regression model to adequately predict the true value of QMED. For hydrological models such as the QMED equation, the model error is often much larger than the sampling error if a reasonable number of years have been used to estimate QMED.

The between-catchment correlations of the individual error terms have very different interpretations for the two types of error. Correlation between sampling errors is a result of rainfall events causing increased flow in neighbouring catchments at the same time. The existence of correlation in model errors, on the other hand, signifies an inability of a particular regression model to adequately represent the true QMED values in neighbouring catchments, that is, the existence of regional clusters of under and over prediction. Notionally, some local geographical effect “causes” the clustering, but this effect is not adequately represented in the catchment characteristics.

While the sampling errors are related to the data-set used for estimation of the QMED values at each individual site, the model errors are specific to a particular regression model. Thus each choice of catchment descriptors will result in its own specific model error structure. Therefore, while the statistical properties of the sampling error can be estimated once and used in all regression models, those of the model error need to be estimated for each regression model tested. Kjeldsen and Jones (2007) showed that the performance of the donor transfer scheme for estimation of QMED is closely related to the model error correlation associated with the QMED equation, hence it was considered important to specify a correct model error structure for the revised QMED equation. The donor transfer scheme for estimation of QMED will be further discussed in Chapter 5.

Estimation of the regression model parameters $\boldsymbol{\theta}$ can be based on, for example, a GLS procedure or the maximum likelihood method. As part of this study, a GLS procedure was developed that enables an exploratory analysis to identify a suitable generic description of the model error correlation. The analysis was based on an iterative procedure involving re-weighting of the regression residuals as detailed in Appendix C and in Kjeldsen and Jones (2008).

Having identified a suitable description of the regression model error structure, estimation of the regression model parameters was based on the maximum likelihood (ML) method. ML estimation was found to be more stable than the GLS procedure. These issues are further discussed in the following two sections, which develop the models used to describe the two types of error.

Sampling error

Both the diagonal as well as the off-diagonal elements of the sampling error covariance matrix $\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}$ are estimated based on consideration of the asymptotic variance of the sampling median, and are given as

$$\Sigma_{\varepsilon,ij} = \begin{cases} 4\beta_i^2 / n_i & i = j \\ 4\beta_i\beta_j \dfrac{n_{ij}}{n_i n_j} r_{\varepsilon,ij} & i \neq j \end{cases} \tag{4.6}$$

where β_i is the scale parameter of the GLO distribution, standardised to have unit median, estimated using L-moments as described by Institute of Hydrology (1999). Here n_{ij} denotes the number of years for which catchments i and j both have data, while n_i and n_j are the total numbers of years of data for the two catchments separately. In addition, estimation of the off-diagonal elements requires estimates of the correlation coefficient between the log-transformed median annual maximum flood for each pair of sites, $r_{\varepsilon,ij}$.

A bootstrap experiment was carried out to investigate the cross-correlation between L-moment ratios at different sites. Bootstrapping is a technique where new samples are created from an original sample by randomly selecting (with replacement) observations from the original sample. Considering the annual maximum series of peak flow from the

602 rural catchments, a total of 11,062 pairs of gauges with a minimum of 40 years of overlapping record were available. To investigate the cross-correlation between the log-median annual maximum peak flow and relate it to geographical distance between catchment centroids, each of these pairs were analysed in turn. For each station pair, a new bootstrap sample was created for the pair by randomly selecting years (with replacement) in the overlapping record. From each selected year, the joint pair of observations was transferred to the joint bootstrap sample, thereby preserving the cross-correlation between the annual maximum series of the two sites. The selection is continued until the new bootstrap sample has a record length equal to the length of the overlapping record in the original sample. From the joint bootstrap sample, the medians of the log-transformed annual maximum peak flows are estimated for both sites and recorded. By creating 1,000 new bootstrap samples for each station pair, the correlation between the log-transformed medians can be estimated and linked to the distance between catchment centroids as

$$r_{\varepsilon,ij} = \phi_1 \exp\left(-\phi_2 d_{ij}\right) + \left(1-\phi_1\right)\exp\left(-\phi_3 d_{ij}\right) \qquad (4.7)$$

where d_{ij} is the distance (km) between centroids of catchments *i* and *j*. The three parameters ϕ_1, ϕ_2 and ϕ_3 are estimated using a least-squares technique. The outcome of the bootstrapping experiment is shown in Figure 4.2. This shows the bootstrapped sample estimates of correlation, together with the correlation function that has been fitted.

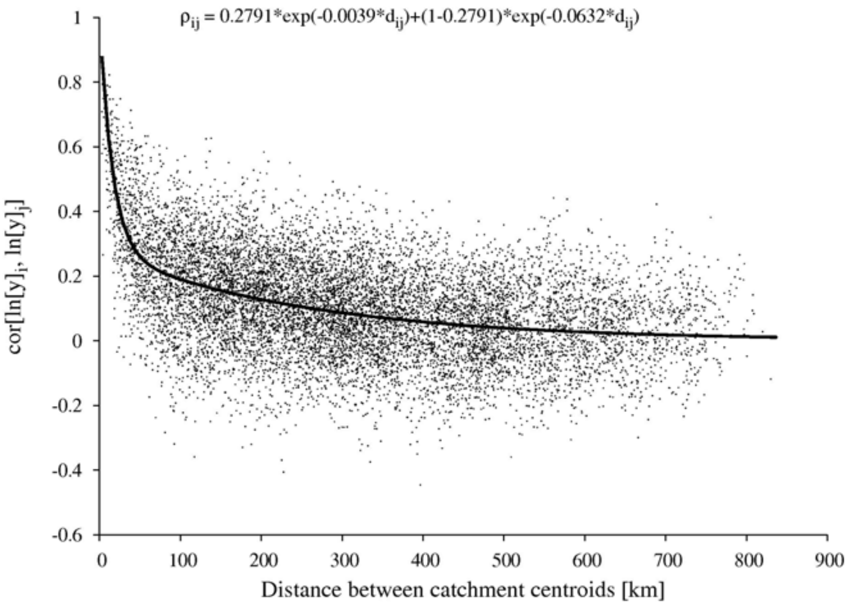


Figure 4.2 Correlation between sampling errors of log-transformed median annual maximum flood as a function of distance between catchment centroids.

Use of the estimator of the at-site sampling variability of the log-median, y, in equation (4.6) involves providing estimates of the population statistics for individual catchments. It was considered appropriate to replace the direct estimates of the GLO scale parameter β in equation (4.6) with corresponding estimates derived using an ordinary least squares (OLS) regression model, linking β to a set of catchment descriptors. Estimates were obtained using the model:

$$\ln[\beta_i] = \alpha_0 + \sum_{p=1}^{P} \alpha_p \ln[x_{i,p}] + \gamma_i \quad (4.8)$$

where P is the total number of catchment descriptors used in the regression model, $\mathbf{x}_{i,p}$ is the value of the *p*'th catchment descriptor for the *i*'th catchment, and α_p is the *p*'th regression model parameter. Only a limited investigation has been made of the errors, γ_i . It should be noted that the results of the OLS regression are reported (Table 4.2) as if these errors can be assumed to be independent and normally distributed with mean zero and variance σ_γ^2 , whereas the errors are very likely to be correlated between catchments. Thus the estimates of the standard errors of the regression parameters are likely to be too small. The use of OLS estimates rather than GLS estimates at this stage is not thought to be important.

Table 4.2 Summary statistics for the regression model describing $\ln[\beta_i]$ which is used to model the variance of the sampling error of the median.

Variable	Coefficient (α_p)	Standard error	t-value	p-value
Intercept (α_0)	-1.1221	0.0664	-16.91	0.000
Ln[AREA]	-0.0816	0.0105	-7.78	0.000
Ln[SAAR/1000]	-0.4580	0.0401	-11.43	0.000
Ln[BFIHOST]	0.1065	0.0520	2.05	0.041
$\sigma_\gamma^2 = 0.107 \quad df = 598 \quad r^2 = 0.28$				

The regression model has an r^2 value of only 28 per cent, which indicates less predictive power than could have been hoped for, but relates to the substantial sampling error in the estimates of the GLO scale parameters. To estimate the sampling covariance $\mathbf{\Sigma}_\varepsilon$, estimates of β obtained through equation (4.8) are substituted into equation (4.6). Using these instead of the sample estimates of β substantially reduces the noise that would otherwise be included. The general effect of this unwanted noise is unclear. It is thought that it will have little effect on the performance of the estimated regression coefficients in the model for the log-median flood, but also that it could have a more important effect on the outcome of procedures for the use of donor sites (Chapter 5) in cases where these might be used for donor catchments with short records.

The outcome of the analysis summarised in Table 4.2 is a route to the construction of the covariance matrix of the sampling errors, $\mathbf{\Sigma}_\varepsilon$, which plays an important role in the GLS procedure.

Model error

As the true values of QMED are unknown, properties of the model error cannot be estimated directly from the data in the same way in which properties of the sampling error were estimated. In the FEH, the existence of the model error correlation was acknowledged and set equal to the correlation between AMAX events using the formula

$$r_{\eta,d} = \exp(-0.016d), \quad (4.9)$$

where d is the geographical distance (in km) between catchment centroids. While this might be a reasonable first approximation, the model error should ideally be estimated separately for each particular regression model under consideration rather than set to a pre-defined value. The issue of a correct description of the model error correlation becomes an important issue when considering the effect of data transfer from donor catchments, as illustrated by Kjeldsen and Jones (2007), and discussed in detail in Chapter 5 of this report.

Therefore, a very important advance in the FEH methodology has been the development of an advanced recursive procedure to identify and specify a suitable model linking the model error correlation to the geographical distance between catchment centroids. An in-depth discussion of the method and application to the HiFlows-UK data set used in this study can be found in Appendix C and in Kjeldsen and Jones (2008). It was found that the relationship between model error correlation and geographical distance could reasonably be described using the same type of function as used to describe the correlation of the sampling errors, i.e. a mixture of two exponential functions:

$$r_{\eta,d} = \varphi_1 \exp\left[-\varphi_2 d\right] + \left(1-\psi\right)\exp\left[-\varphi_3 d\right], \tag{4.10}$$

where φ_1, φ_2 and φ_3 are model parameters that must be estimated for each individual regression model.

Final estimation of regression parameters

Having specified the error structure, the regression model parameters can be estimated using a maximum-likelihood procedure, which incorporates what are essentially the steps involved in calculating the GLS estimates of the regression parameters. If it is assumed that the regression residuals are normally distributed with mean zero and a total covariance matrix, $\sigma_\eta^2\mathbf{G}$, described in equation (4.5), the objective of the overall estimation procedure is to minimise the negative log-likelihood function

$$-\ln\left(L_k\right) = \frac{1}{2}\ln\left[\det\left(\sigma_\eta^2\mathbf{G}\right)\right] + \frac{1}{2}\left(\mathbf{y}-\mathbf{X}\boldsymbol{\theta}\right)^{\mathrm{T}}\left(\sigma_\eta^2\mathbf{G}\right)^{-1}\left(\mathbf{y}-\mathbf{X}\boldsymbol{\theta}\right) \tag{4.11}$$

with respect to the three model error correlation parameters (φ_1, φ_2 and φ_3), the model error variance (σ_η^2) and the regression parameters ($\boldsymbol{\theta}$). The problem is simplified by noting that, for given values of σ_η^2, φ_1, φ_2 and φ_3 (which between them determine $\mathbf{G}$), the value of $\boldsymbol{\theta}$ which minimises (4.11) is given the least squares estimator (specifically the GLS estimator)

$$\hat{\boldsymbol{\theta}} = \left(\mathbf{X}^{\mathrm{T}}\mathbf{G}^{-1}\mathbf{X}\right)^{-1}\mathbf{X}^{\mathrm{T}}\mathbf{G}^{-1}\mathbf{y}\,. \tag{4.12}$$

Thus, estimation by maximum likelihood can be implemented as a search over the four parameters σ_η^2, φ_1, φ_2 and φ_3.

In reporting the results of the estimation, in particular for the uncertainties of the regression coefficients, the course adopted here has been to quote results from a final GLS analysis that is based on the optimised parameter values. The consequence of this is that the uncertainties reported (the standard errors and the implied tests of significance related to these) ignore the effects that derive from the estimation of the other parameters. This has the advantage of simplicity and should not prove too misleading in the present context where the uncertainties are used for guidance only. It also has the advantage of allowing a simple summary of the model which can be compared to the equivalent from other models. However, when undertaking the search of the variables to be included in the model for QMED, checks of the improvement (or otherwise) of the model by including selected candidate variables were made in the form of a likelihood-ratio test comparing the optimised values of the log-likelihood (equation (4.11)) for models including and excluding the candidate. Thus the variable selection analysis has not relied on the approximation used to report and summarise the final model.

4.4 Variable selection

Selecting the combination of catchment descriptors to be included in the final QMED model was a lengthy iterative process and, just as in the FEH, not every stage of the procedure is reported here. Throughout the process, the FEH QMED equation has been used as a benchmark against which other possible candidates could be judged.

4.4.1 The FEH QMED equation

The FEH QMED equation was developed based on a comprehensive analysis as reported in the FEH (Institute of Hydrology, 1999). For the present study, the first step in the search for an improved model was to re-estimate the parameters using the GLS method based on the 602 catchments taken from the HiFlows-UK dataset as desribed in Chapter 2. The summary statistics for the regression model are shown in Table 4.3.

Table 4.3 Summary statistics for the FEH regression model for ln[QMED].

Variable	Coefficient (θ_p)	Standard error	t-value	p-value
Intercept	0.1066	0.1802	0.59	0.554
Ln[AREA]	0.9775	0.0572	17.08	0.000
Ln[AREA]^2	-0.0122	0.0056	-2.16	0.031
Ln[SAAR/1000]	1.7612	0.0913	19.29	0.000
Ln[FARL]	3.7940	0.2753	13.78	0.000
Ln[SPRHOST/100]	1.0864	0.0479	22.70	0.000
RESHOST	-3.7266	0.4020	-9.27	0.000
$\sigma_\eta^2 = 0.1543$, *df* = 595, r^2 = 0.938 (log scale)				

From the results in Table 4.3 it appears that the (ln[AREA])^2 term added to the FEH QMED equation is less significant when estimating the QMED model using the updated HiFlows-UK data than with the dataset used in the FEH study (FEH, Vol. 3, Table 13.7). The rationale for adding the term was that early investigations of model residuals in the FEH study suggested a non-linear effect due to catchment size. A similar effect was not detected in this study, but rather a non-linearity effect due to catchment average annual rainfall, which was also evident from the residual plots reported in the FEH (Vol. 3, Figure 13.8), as will be discussed later.

4.4.2 Comprehensive search results

An exhaustive search procedure was used as a screening tool to identify potentially useful combinations of catchment descriptors. The search was based on ordinary least squares (OLS) rather than the more comprehensive GLS methodology developed in this study The search was restricted to a relatively small set of descriptors, where selection was based on the variables reported as most useful by the FEH study, together with the new descriptors developed for the present study. A summary of the results is presented in Table 4.4, and a discussion of these results follows.

Table 4.4 Best fitting OLS models using from one to 12 catchment descriptors

	LnAREA	lnSAAR	lnBFIHOST	BFIHOST	lnFARL	lnPROPWET	lnDPSBAR	lnFPEXT	lnPRAT	lnRMED(1day)	lnEVAP	R^2
1	****	-	-	-	-	-	-	-	-	-	-	0.520
1	-	-	-	-	-	****	-	-	-	-	-	0.393
1	-	-	-	****	-	-	-	-	-	-	-	0.301
2	****	-	-	-	-	****	-	-	-	-	-	0.818
2	****	-	-	****	-	-	-	-	-	-	-	0.804
2	****	****	-	-	-	-	-	-	-	-	-	0.794
3	****	****	-	****	-	-	-	-	-	-	-	0.912
3	****	-	-	****	-	-	-	-	-	****	-	0.904
3	****	-	-	****	-	****	-	-	-	-	-	0.901
4	****	****	-	****	****	-	-	-	-	-	-	0.936
4	****	-	-	****	****	-	-	-	-	****	-	0.923
4	****	****	****	-	****	-	-	-	-	-	-	0.923
5	****	-	-	****	****	****	-	-	-	****	-	0.941
5	****	****	-	****	****	-	****	-	-	-	-	0.940
5	****	****	-	****	****	-	-	-	****	-	-	0.940
6	****	-	****	****	****	****	-	-	-	****	-	0.944
6	****	****	****	****	****	-	****	-	-	-	-	0.943
6	****	****	****	****	****	-	-	-	****	-	-	0.943
7	****	****	****	****	****	****	-	-	-	****	-	0.946
7	****	****	****	****	****	-	****	-	****	-	-	0.946
7	****	-	****	****	****	****	****	-	-	****	-	0.945
8	****	****	****	****	****	****	-	****	-	****	-	0.947
8	****	****	****	****	****	****	****	-	-	****	-	0.947
8	****	****	****	****	****	****	-	-	****	****	-	0.947
9	****	****	****	****	****	****	-	****	****	****	-	0.948
9	****	****	****	****	****	****	****	-	****	****	-	0.948
9	****	****	****	****	****	****	****	****	-	****	-	0.947
10	****	****	****	****	****	****	****	-	****	****	****	0.948
10	****	****	****	****	****	****	****	****	****	****	-	0.948
10	****	****	****	****	****	****	-	****	****	****	****	0.948

Note that the two variables Ln[SPRHOST] and RESHOST used in the FEH QMED equation are not included in the results reported here although they did feature in earlier stages of this study. Previous studies (Kjeldsen *et al*. 2005) have found SPRHOST to be a less efficient descriptor of hydrological soil properties than BFIHOST, and RESHOST was found to lack a clear physical interpretation. Hence Ln[BFIHOST] and BFIHOST have been included as candidate descriptors in preference to the variables appearing in the FEH QMED equation.

The search procedure tests every possible combination of catchment descriptors by fitting the OLS regression and notes the resulting coefficient of determination (r^2) for each combination. Table 4.4 shows the three best models, in terms of r^2, that use from one to 10 different catchment descriptors

From the results in Table 4.4 it can be observed that the first five catchment descriptors (ln[AREA], ln[SAAR], ln[BFIHOST], BFIHOST and ln[FARL]) seem to occur more frequently in the model selection than the remaining descriptors. While it can be argued that ln[PROPWET] and ln[RMED(1day)] also occur relatively frequently, both these descriptors are highly correlated with ln[SAAR].

4.4.3 Investigation of residuals

Figure 4.3 shows some scatter plots that relate to development of the final model for QMED, in terms of selecting which descriptors should be included in the model equation and the form that this inclusion should take. Each scatter plot shows (on the y-axis) the residuals from a given model (fitted using GLS) plotted against (on the x-axis) selected individual catchment descriptors. In these plots, interest centres on the following features.

- The extent of any relationship between the residuals and descriptors not already included in the model, since this would indicate that that descriptor would improve the predictions.
- The possible presence of a curved pattern in the residuals when plotted against any descriptors (included or not in the model), since this would indicate the potential usefulness of considering other transformations of the descriptors.

The present study has examined more complete sets of such plots, but Figure 4.3 presents a simplified set that relates specifically to the final model selected, as described below.

The results from the initial analysis strongly suggest that a QMED equation based on the four descriptors ln[AREA], ln[SAAR], ln[FARL] and ln[BFIHOST] (row 3 in Figure 4.3) fits the data well without using too many spurious parameters. However, a visual inspection of the residuals from this particular model suggested a non-linear effect in the relation of the residuals to both ln[SAAR] and ln[BFIHOST]. Both of these effects were further investigated by estimating regression models of increasing complexity and plotting the resulting residuals against the different catchment descriptors, as shown in Figure 4.3. The first model in Figure 4.3 (row 1) is based on ln[AREA] only, and illustrates the need for including rainfall (SAAR), soil properties (BFIHOST) and upstream reservoir influence (FARL) in the model, as strong patterns can be observed when the model residuals are plotted against these catchment descriptors.

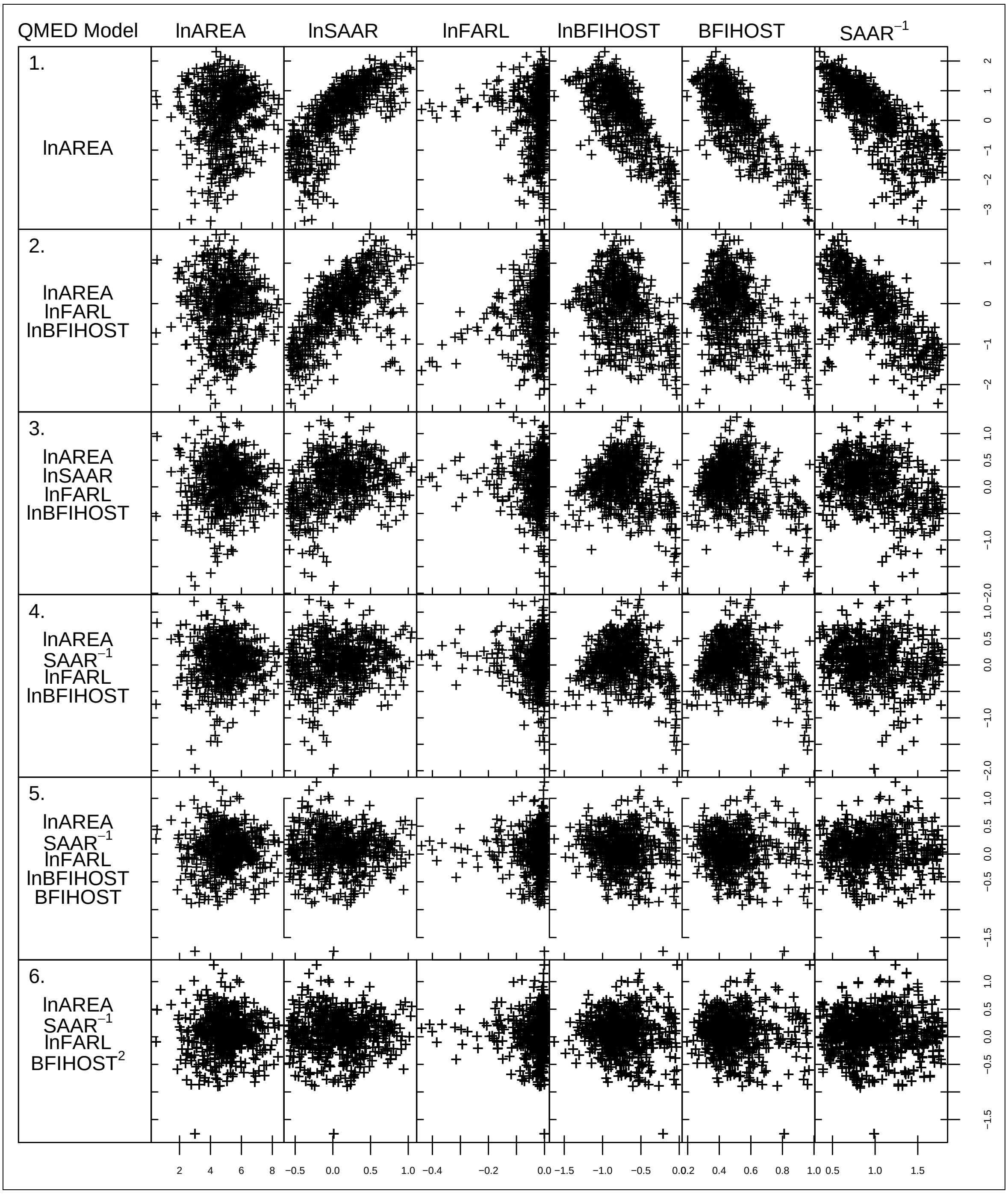


Figure 4.3 Relationship between regression residuals ($\ln[QMED_{obs}]$-$\ln[QMED_{cds}]$) and selected catchment descriptors for regression models of increasing complexity.

The data analysis proceeded in a number of steps, illustrated here using Figure 4.3, though a wider set of variables was actually considered. Firstly, the non-linear effects of ln[SAAR] were investigated. The model defined in row 2 of Figure 4.3 illustrates the effect of not including ln[SAAR] in the QMED model by using only ln[AREA], ln[FARL] and ln[BFIHOST] to explain QMED.

In row 3 of Figure 4.3, ln[SAAR] has been added to the model in row 2, and any effect of ln[SAAR] on the residuals should be removed unless non-linear effects are present. By comparing the plots of the residuals against ln[SAAR] from the two models, it is clear that when moving from the second to the third model (i.e. adding the ln[SAAR] term) most of the structural dependence on ln[SAAR] is removed, although evidence of a non-linear effect can be observed in the slight curvature of the residuals when plotted against both ln[SAAR] and SAAR^{-1} . A similar shape of the residuals when plotted against ln[SAAR] appears to have been produced when the FEH QMED equation was developed, as can be observed in FEH Vol.3, Figure 13.8. However, the FEH did not include the non-linear terms ln[SAAR]^{2} in the final QMED equation as it was found not to be significant. Comparing different options for inclusion of a non-linear SAAR term, the single term SAAR^{-1} was found to perform well and was subsequently introduced into the final QMED equation. The effect of introducing SAAR^{-1} rather than ln[SAAR] can be observed by comparing row 3 and row 4 in Figure 4.3, where using SAAR^{-1} (row 4) removes the tendency for the residuals to curve when plotted against ln[SAAR].

Next, the non-linear effects of ln[BFIHOST] were investigated. Using the model in row 3, it can be observed that including ln[BFIHOST] alone does not remove all the effect of BFIHOST from the residuals, especially at high values of BFIHOST, i.e. the model does not adequately describe the behaviour of QMED on permeable catchments. As with SAAR, several options for introducing a non-linear BFIHOST term were considered. The two models in row 5 and row 6 compare two options that were found to perform well. Row 5 uses both ln[BFIHOST] and BFIHOST (untransformed), which is broadly equivalent to the FEH QMED equation using both ln[SPRHOST] and RESHOST. However, a simpler model (row 6) using only BFIHOST^{2} (untransformed) was found to perform better and was therefore the preferred option.

It is generally considered that the QMED equation is most often applied to catchments whose areas are in the lower range of those represented in the data set used to fit the model, and indeed can be somewhat smaller. Ideally, the dataset used for model fitting would include many more catchments having areas typical of applications of the FEH methodology. In the absence of such data, all that can be done is to pay special attention to this point and consider whether the data suggests the need for some alternative structure to the regression equation that might provide a better fit for catchments having small areas. Within the present study, examination of residual plots (such as in Figure 4.3) has not indicated any such possibilities for improvement. In addition, consideration of new variables constructed as combinations (products etc) of the main set of catchment descriptors, as in the FEH study, has not yielded improvements to the model. The relevance of this is that it provides a means of looking for effects that might occur for particular combinations of catchment descriptors, for example small AREA with low BFIHOST.

4.5 Estimating a new QMED model

Having decided on the four catchment descriptors to be included, the final QMED equation is estimated based on minimisation of the negative log-likelihood function in equation (4.11). The summary statistics of the resulting regression model are shown in Table 4.5.

Table 4.5 Summary statistics for the final QMED model.

Variable	Coefficient (θ_p)	Standard error	t-value	p-value
Intercept (θ_0)	2.1170	0.1172	18.06	0.000
Ln[AREA]	0.8510	0.0114	74.35	0.000
(SAAR/1000)$^{-1}$	-1.8734	0.0968	-19.35	0.000
Ln[FARL]	3.4451	0.2654	12.98	0.000
BFIHOST^{2}	-3.0800	0.1158	-26.60	0.000
$\sigma_\eta^2 = 0.1286$, *df* = 597, r^2 = 0.945				

The results in Table 4.5 show that all the variables are highly significant (very low p-values). The final model for prediction of QMED at ungauged sites is given by

$$\ln[QMED] = 2.1170 + 0.8510\ln[AREA] - 1.8734\left(\frac{1000}{SAAR}\right) + 3.4451\ln[FARL] - 3.080BFIHOST^{2}$$

$$QMED = 8.3062AREA^{0.8510}0.1536^{\left(\frac{1000}{SAAR}\right)}FARL^{3.4451}0.0460^{BFIHOST^{2}}\ . \qquad (4.13)$$

This model has a factorial standard error (*fse*) of

$$fse = \exp(\sigma_{\eta}) = \exp\left(\sqrt{0.1286}\right) = 1.431\,. \qquad (4.14)$$

The original FEH QMED model reported an *fse* value of 1.546. Fitting the six variables used in the original FEH model, but using the HiFlows-UK dataset gives a factorial standard error of 1.480. Using the QMED model results in an improvement of about 7.5 per cent in *fse* compared to the original FEH model. The effect of this reduction on the widths of confidence intervals for QMED is discussed in Section 4.6.2.

The pattern of the coefficients and transformations in equation (4.13) can be given a simplified interpretation as follows.

- QMED rises with increasing AREA.
- QMED rises with increasing SAAR.
- QMED rises with increasing FARL (which means it increases with decreasing flood attenuation, and decreases with more attenuation of flood peaks).
- QMED drops with increasing BFIHOST, and decreases more strongly when the baseflow component is highest.

Thus the general interpretation of the model is hydrologically acceptable.

The model error correlation, which will be used later when discussing the use of data transfer from donor and analogue catchments, is estimated as part of the maximum likelihood procedure and given as

$$r_{\eta,ij} = 0.4598\exp(-0.0200d_{ij}) + (1-0.4598)\exp(-0.4785d_{ij}), \qquad (4.15)$$

where d_{ij} is the geographic distance between the centroids of two catchments. The modelling error represents the inability of the relatively simple regression type model used here to represent the complex behaviour of real catchments. Describing the correlation between the model errors as a function of geographical distance therefore represents regional patterns of the model's inability, which would lead to regional clusters of positive and negative QMED residuals. It is important to note that the regression modelling error can only be removed or, more likely, reduced by introducing more and better catchment descriptors in the regression model.

A pair of regression diagnostics plots investigating the assumption of Normally distributed residuals is shown in Figure 4.4. This allows a comparison to be made between the results obtained by analysising the HiFlows-UK data with those from the FEH. On comparing these residual plots, it is clear that the assumption of Normally distributed residuals is a better match to the observations using the HiFlows-UK data than in the original FEH study. Note that the FEH plot shows GLS residuals derived as part of the GLS procedure while that for the present study shows raw residuals. However, this makes little numerical difference and the visual comparison is still informative. One low outlier can be identified on the regression diagnostics plot in

Figure 4.4 for this study. The particular gauging station is 44008 (South Winterbourne at Winterbourne Steepleton), where, following the project's review of the HiFlows-UK data for this site, the early part of the record was rejected and only the more recent part of the record was used (12 annual maximum flood peaks in all). However, compared to the magnitude of the residuals at the tail-end of the corresponding regression diagnostic plot from the FEH, the outlying residual value for catchment 44008 does not cause particular concern.

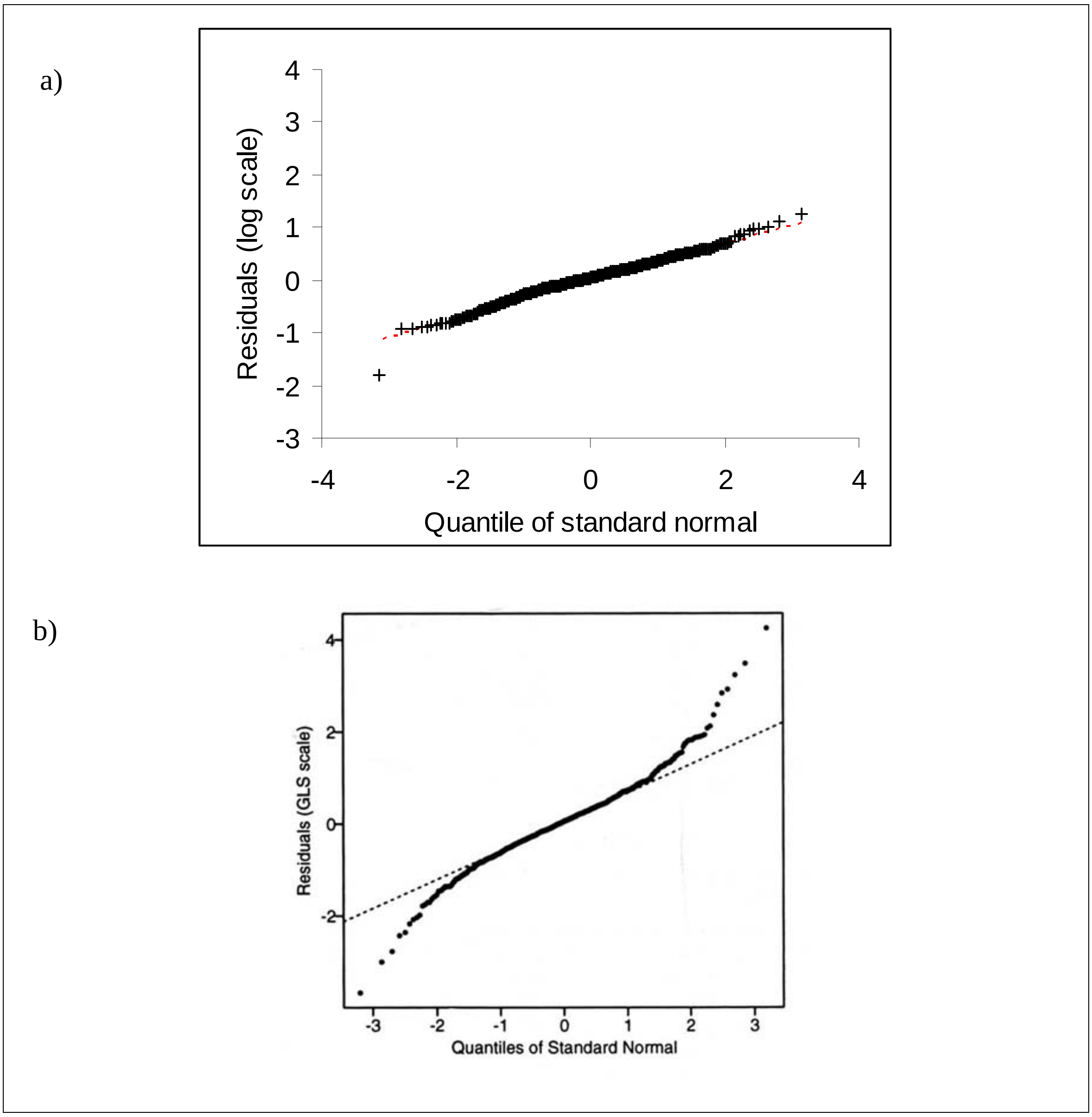


Figure 4.4 Regression diagnostic plot investigating normality of residuals: a) QMED model developed in this study, and b) Figure 13.6 FEH Vol.3 (Institute of Hydrology, 1999).

To further compare the model derived using the HiFlows-UK data with the original FEH study, Figure 4.5 shows the fitted values and residuals for the fitted model (log scale) and the corresponding figures from FEH Vol.3.The similarity between the two sets of plots in Figure 4.5 indicates that the results obtained in this study compare well with the findings of the FEH. While the two sets of plots relate to different sets of catchments, the ranges of values of ln[QMED] are very similar between the two sets.

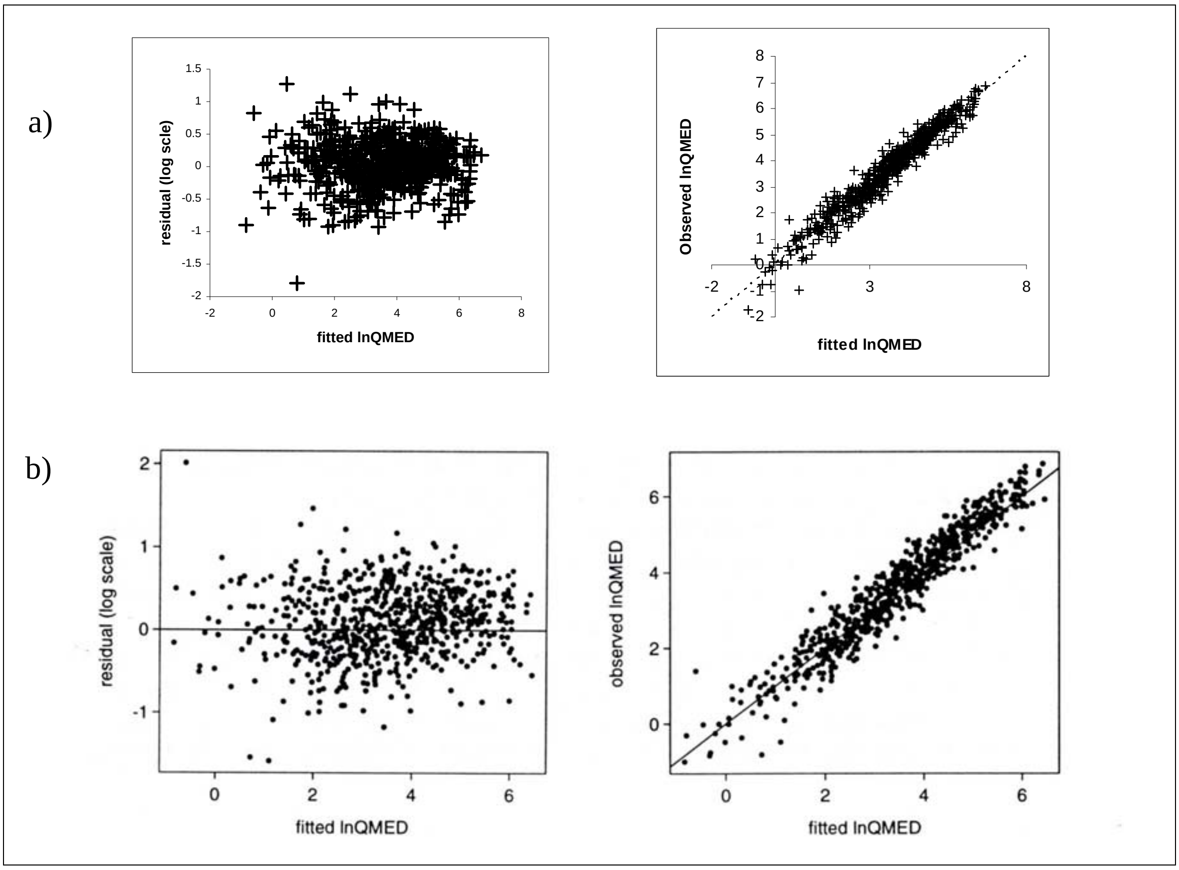


Figure 4.5 Fitted values and residuals for the fitted model (log scale): a) HiFlows-UK data and b) reproduction of Figure 13.7 FEH Vol. 3 (Institute of Hydrology, 1999).

4.6 Comparison between the new model and the FEH model

The differences between the new QMED model developed in this study and the FEH QMED model are assessed by investigating the difference in i) estimates of QMED and ii) the uncertainty of the estimates.

4.6.1 Comparison of QMED estimates

A comparison between estimates of QMED obtained using the new QMED equation, equation (4.13), and the original FEH QMED equation, is presented in Figure 4.6. This shows the ratio of the two estimates for each of the 602 catchments used in this study.

Note that the catchments included in Figure 4.6 include only rural catchments, hence the relatively large geographical regions in England without any coverage. From this figure it is clear that the new QMED equation gives lower estimates of QMED in the East and South Eastern parts of England, but generally higher estimates in the Western and Northern parts of the UK.

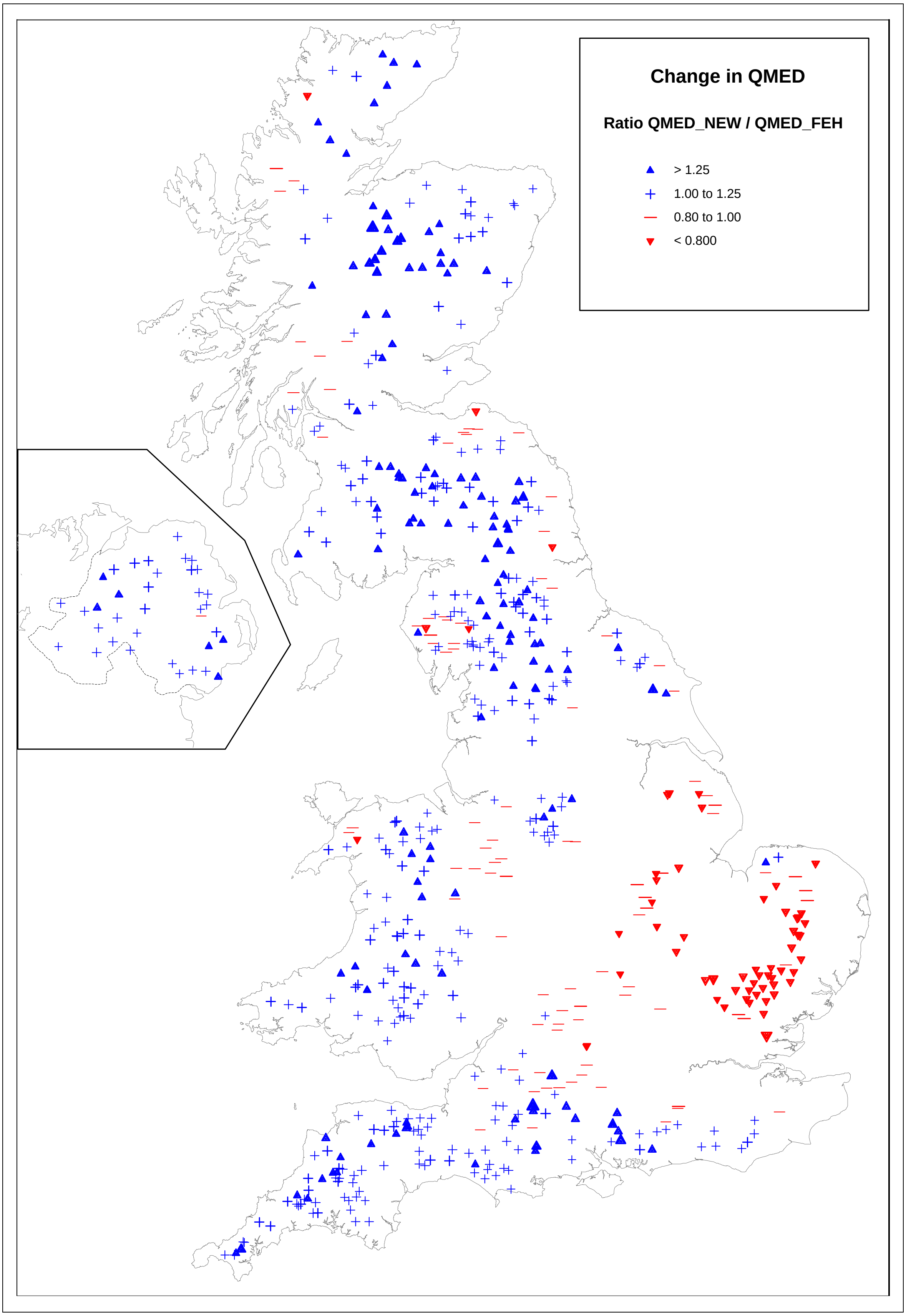


Figure 4.6 Comparison of QMED estimates obtained from catchment descriptors only using i) the new QMED equation and ii) the FEH QMED equation.

The results in Figure 4.6 can be summarised by the statement that the changes in QMED range from factors of 0.55 to 2.01, with half being greater than 1.15 (25 per cent of the ratios are less than 1.00 and 25 per cent are greater than 1.24). Here a factor greater than one means that estimates of QMED from the new equation are greater than the estimates given by the equivalent FEH equation. Overall, the new estimates are larger than the FEH estimates in 75 per cent of catchments.

4.6.2 Comparison of uncertainty of QMED

As ln[QMED] can be considered log-Normally distributed, the 68 per cent and 95 per cent confidence intervals are as follows.

- 68% confidence interval (QMED/*fse*, QMED × *fse*)
- 95% confidence interval (QMED/fse^2, QMED × fse^2)

While a 7.5 per cent reduction in *fse* might appear small, the effects on the relative width (width/QMED) of the 68 per cent and 95 per cent confidence intervals are reductions of 19 and 21 per cent, respectively, when comparing the new model with the FEH model.

Consider an example where the value of QMED is predicted at a location with grid coordinates (580550, 223300) where the FEH CD-ROM version 2.0 gives the following catchment descriptors:

AREA = 150 km^2, *SAAR* = 578 mm, *FARL* = 0.994,

BFIHOST = 0.496, *SPRHOST* = 38.9%, *RESHOST* = 0.0147.

The resulting estimates of QMED and upper and lower bounds for both the 68 per cent and 95 per cent confidence intervals are shown in Table 4.6.

Table 4.6 Comparison of catchment descriptor estimates of QMED using the new and the FEH models. All units are m^3s^{-1}.

QMED model	QMED [m^3s^{-1}]	68%		95%	
		Lower	Upper	Lower	Upper
FEH model	16.1	10.4	24.9	6.7	38.5
New model	10.7	7.5	15.3	5.2	21.8

A comparison of the uncertainties of the new and old models using Table 4.6 is complicated by the fact that the two models give different estimates of QMED. Table 4.7 provides a comparison for a notional case in which the two models happened to give the same estimate for QMED. It can be seen that the width of the 68 per cent confidence interval has been reduced from 18 m^3s^{-1} to 14.6 m^3s^{-1} (a reduction of 18 per cent), while the width of the 95 per cent confidence interval has been reduced from 39.4 m^3s^{-1} to 31.2 m^3s^{-1} (a reduction of 20 per cent).

Table 4.7 Comparison of the uncertainties of estimates of QMED using the new and the FEH models. All units are m^3s^{-1}

QMED model	QMED [m^3s^{-1}]	68%		95%	
		Lower	Upper	Lower	Upper
FEH model	20	12.9	30.9	8.4	47.8
New model	20	14.0	28.6	9.8	41.0

5 Use of donor sites

When conducting a flood frequency analysis at an ungauged site, the FEH strongly recommends transferring data from catchments judged to be hydrologically similar to the target site but for which annual maximum flood data are available. However, in a comprehensive assessment of the FEH statistical method, Morris (2003) found inappropriate adjustment of QMED using donor and analogue catchments to be a major source of potential error. Morris' study also identified regional patterns in the QMED residuals and suggested that considerations of on-line or off-line donors could potentially enhance the adjustment procedure. In a separate study, Kjeldsen and Jones (2007) analysed the benefits of using data transfer from donor sites from the perspective of reducing prediction variance at the site of interest. The results obtained by Kjeldsen and Jones (2007) enable a more analytical approach than that of Morris (2003) and the resulting improved data transfer scheme is presented below.

5.1 FEH donor adjustment

Once a suitable donor site has been identified, the index flood at the site of interest is estimated as

$$QMED_{s,adj} = QMED_{s,cds} \frac{QMED_{g,obs}}{QMED_{g,cds}}, \tag{5.1}$$

where subscript *s* refers to the ungauged target (or subject) site and *g* the gauged donor site, and the subscript *cds* refers to the estimates derived from catchment descriptors at the gauged and target sites, *obs* the observed value at the gauged site and *adj* the adjusted value at the target site. While this adjustment assumes the residuals from the QMED equation at both the target and the donor site exhibit the same behaviour, the recommended procedure makes no use of the distance-based relationship for the modelling-error correlation that is included in the FEH GLS-model.

5.2 New data transfer scheme

A major advance from the FEH statistical method developed as part of this project is the ability to identify and estimate a separate model for the model error correlations (Kjeldsen and Jones, 2008). This is shown for the new QMED model in equation (4.15). Kjeldsen and Jones (2007) defined a revised data transfer scheme as an alternative to that suggested by the FEH study, which is introduced here as the "new data transfer scheme" and is given as

$$QMED_{s,adj} = QMED_{s,cds} \left(\frac{QMED_{g,obs}}{QMED_{g,cds}} \right)^{a}, \tag{5.2}$$

where the new parameter *a* is estimated by minimising the prediction variance of (the logarithm of) $QMED_{s,adj}$, and is given by

$$a = r_{\eta,sg} \frac{\sigma_\eta^2}{\sigma_\eta^2 + h_{gg}}, \tag{5.3}$$

where σ_η^2 is the model error variance estimated as part of the maximum likelihood estimation procedure of the QMED equation, h_{gg} is the sampling variance of lnQMED$_g$ and $r_{\eta,sg}$ is the model error correlation between the target (s) and the donor (g) sites calculated using the model specified in equation (4.15) (i.e. based on the geographical distance between the target and the donor site). The sampling error of lnQMED (h_{gg}) derived from observed AMAX data is normally much smaller than the model error variance (provided that the donor catchment has a reasonably long record) and thus, for most practical purposes, the *a* parameter in equation (5.3) reduces to $a = r_{sg}$. If the donor adjustment procedure were to be applied where the donor record is short, then values of h_{gg} would be obtained via equations (4.6) and (4.8), with the coefficients shown in Table 4.2.

5.3 Using the network structure

Intuitively, the FEH donor scheme is expected to perform better if the donor catchment is located on the same stream as the target site, which was confirmed by Morris (2003) in the results presented in his report in Table 5.2 (page 55). The new data transfer scheme, as presented above, does not explicitly take into account whether a donor site is located on the same stream as the target site or not. The only quantity needed to estimate the weighting parameter a is the geographic distance between catchment centroids. However, catchments sharing parts of the same river network tend to have centroids located close together.

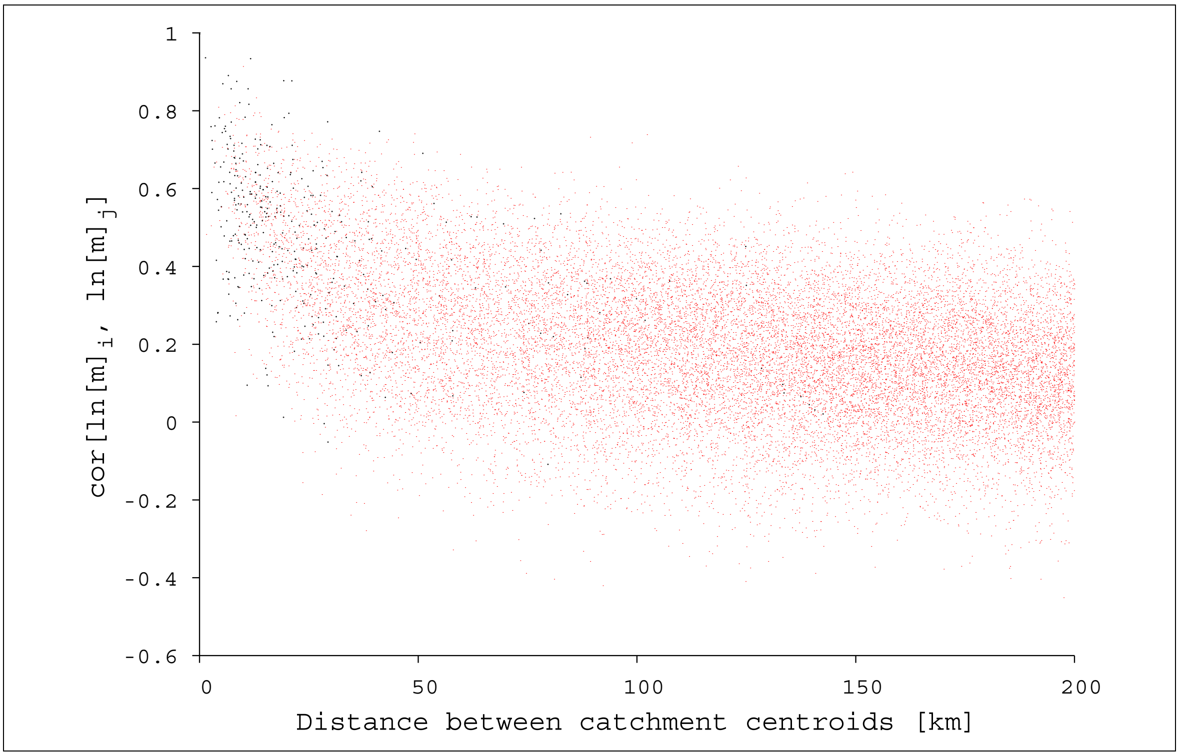


Figure 5.1 Sampling correlation between AMAX series with more than 39 years of data. Black dots show pairs of catchments located on the same river network and red dots show non-network-sharing catchment pairs.

To further investigate the potential benefits of including information about the network structure, the sampling correlation between AMAX series at different sites was considered. Figure 5.1 shows the correlation between log-QMED at different sites with more than 39 years of overlapping records plotted against distance between catchment centroids.

The black dots indicate pairs of sites that are located on the same river network while the red dots indicate pairs that are not. Of course, there are far more red than black dots, but note that the black dots are mostly confined to the left side of the plot. This is because catchments sharing the same network are likely to be geographically close to each other. For the purpose of this project, it was not considered feasible to further investigate the potential for developing separate model error correlation models for the cases in which a donor is located either on the same river network as the subject site or not. However, the conclusion drawn from Figure 5.1 is that there is no clear difference in the patterns of correlation-against-distance for the two cases, and thus that the simple procedure outlined in Section 5.2 should be used in all cases.

5.4 Performance

The effect of data transfer when predicting QMED for ungauged catchments has been investigated based on estimates of QMED obtained for each of the 602 catchments used in this study. The following four approaches to estimation of QMED were tested.

- Using only the regression model in equation (4.13) predicting QMED based on catchment descriptors only.
- Identifying the geographically closest (catchment centroids) out of the 601 other gauged catchments and using the new data transfer procedure in equation (5.2).
- Identifying the donor as above (i.e. the geographically closest catchment), but using the FEH data transfer procedure (equation 5.1).
- Identifying the closest of the 601 other gauged catchments in terms of hydrological similarity as defined by the FEH (i.e. using ln[AREA], ln[SAAR] and BFIHOST).

To assess the performance of each of the three data-transfer methods outlined above, the root mean square error (*RMSE*) was derived for each method as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{M}\left(\ln QMED_{s,adj,i} - \ln QMED_{g,i}\right)^2}{M-5}}, \qquad (5.4)$$

where the subscripts s, g and adj are described in a previous section. The degree of freedom is M-5 = 602 – 5 = 597 corresponding to the five regression parameters in the QMED model. The resulting *RMSE* values obtained for each of the three options are shown in Table 5.1, where it can be observed that, while the new data transfer method improves the *RMSE* when compared to using regression only, the FEH data transfer scheme has a higher *RMSE* than regression only. The latter finding indicates that, on average, the FEH data transfer scheme does not improve the prediction of QMED. The high *RMSE* value (0.475) obtained when using a donor site identified based on hydrological similarity clearly shows that this method is not performing well. In fact, it performs much worse than the regression model alone without any donor transfer.

Table 5.1 RMSE for each of the three methods predicting QMED in ungauged catchments.

Method	RMSE
Regression only, equation (4.13)	0.357
New data transfer	0.327
FEH data transfer: Geographically close	0.377
FEH data transfer: Hydrological similarity	0.475

To further investigate the structure of the *RMSE* values, the 602 catchments were divided into 20 groups according to the distance between a particular catchment and its closest donor catchment. Each of the 20 groups span a distance of 1 km and within each group the *RMSE* was estimated as

$$RMSE_i = \sqrt{\frac{1}{M_i}\sum_{j=1}^{M_i}\left(\ln QMED_{s,adj,j} - \ln QMED_{j,obs}\right)^2} \ , \tag{5.5}$$

where M_i is the number of catchment pairs in the i'th group. For each of the first three methods in Table 5.1, the *RMSE* was estimated for each of the 20 groups and the results plotted on Figure 5.2.

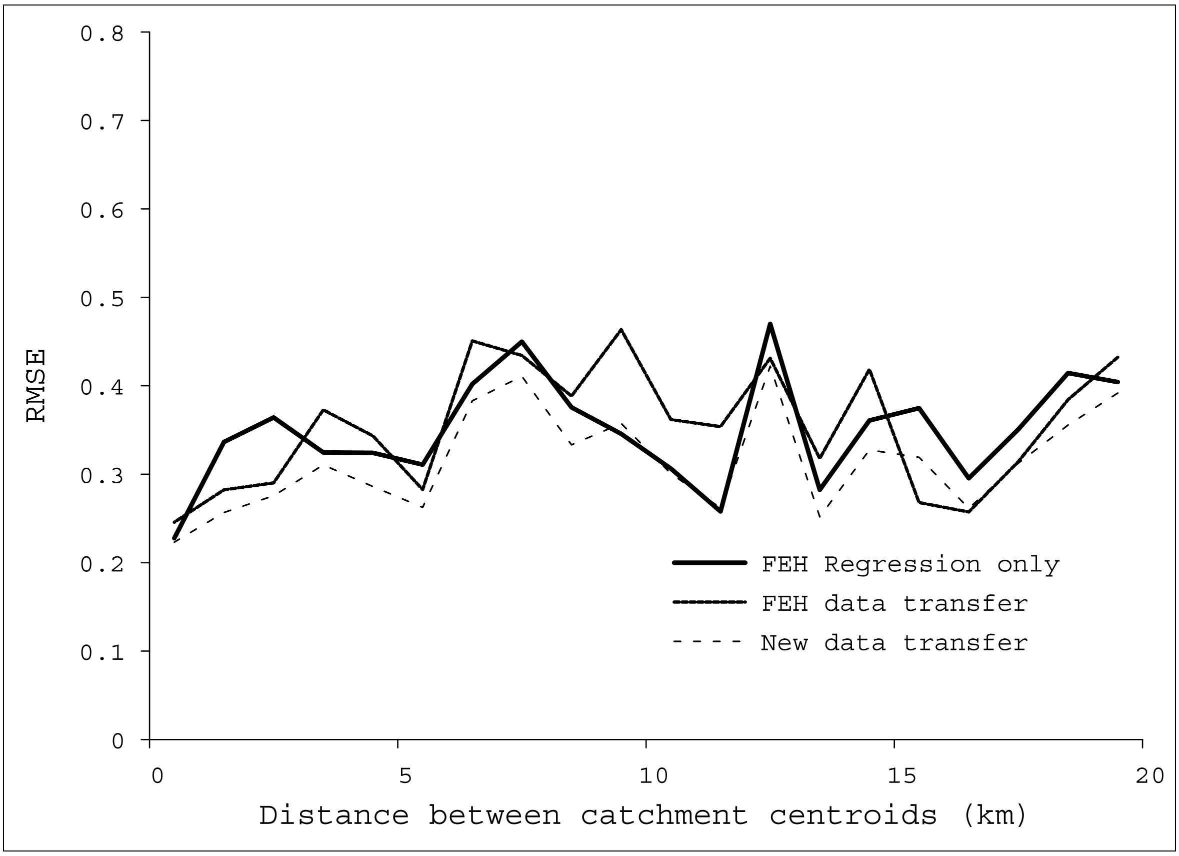


Figure 5.2 RMSE for 1 km intervals in distance between target and donor sites.

As observed on Figure 5.2, the *RMSE* derived using the regression model only is relatively independent of distance. Both the FEH and the new transfer scheme have improved the prediction of QMED compared to using a regression-only approach for very short distances less than 3 km. In general, the new transfer scheme consistently performs better than both the regression-only option and the FEH data transfer scheme, whereas the FEH method often gives higher *RMSE* values than the regression model alone. This is confirmed by the average *RMSE* values reported in Table 5.1.

The FEH-related transfer methods included in Table 5.1 may not be considered immediately representative of the adjustments being made by practitioners since these often involve several catchments and a mixture of both “donors” (geographically close) and “analogues” (hydrologically similar) catchments. Given the scope for personal choice in selecting the contributing catchments, it would be impossible to construct an automatic procedure to represent this more closely. Nevertheless, the results here provide evidence that the use of “analogue” (hydrologically similar) catchments in the data transfer methodology is likely to make estimates of QMED worse, rather than better.

5.5 Discussion of data transfer

The introduction in this study of a distance-based weighting scheme applied to the data transfer ratio is consistent with many of the recommendations made by Morris (2003) following a comprehensive review of the performance of the FEH statistical method. Firstly, the model in equation (4.15), describing the model error correlation as a function of geographical distance, is a direct consequence of the inability of a simple regression model using aggregated catchment descriptors to fully represent the hydrology of complex real catchments and to reflect the regional patterns in this inability. The only option for removing the model error is to improve the regression model by introducing improved catchment descriptors. Secondly, Morris (2003) suggested weighting the donor adjustment coefficients based on catchment similarity (as measured using ln[AREA], ln[SAAR] and BFIHOST). However, as shown in Table 5.1, a method where the weight is based on geographical distance (as in this study) should be the preferred option, rather than a method where the choice of donor is based on catchment similarity. Thirdly, it was suggested by Morris (2003) that consideration of whether the target and donor catchments are located on the same river network or not (on-line or off-line) could potentially help to reduce prediction errors further. While this effect has not been studied exhaustively here, the geographical distance between centroids for catchments located on the same river network is generally small, i.e. the weighting parameter derived from an on-line donor catchment is likely to be relatively high in the new transfer scheme. Further investigations would require scale considerations, such as questions as to whether data from a small unregulated tributary should be used to adjust QMED for a large regulated main river and vice versa.

5.6 Example: donor transfer

In the example provided in Section 4.6.2, QMED was estimated at an ungauged site with grid coordinates (580550, 223300) and the resulting estimates of QMED with associated confidence intervals shown in Table 4.6. Here an example of the new donor transfer procedure is presented by considering a number of possible donor sites for the subject site. Figure 5.3 shows the location of the target site as well as the location of three on-line donors and four off-line donors selected based on the similarity to the subject site in terms of AREA, SAAR and BFIHOST.

Details of the subject catchment for this example and all the potential donor catchments are shown in Table 5.2.

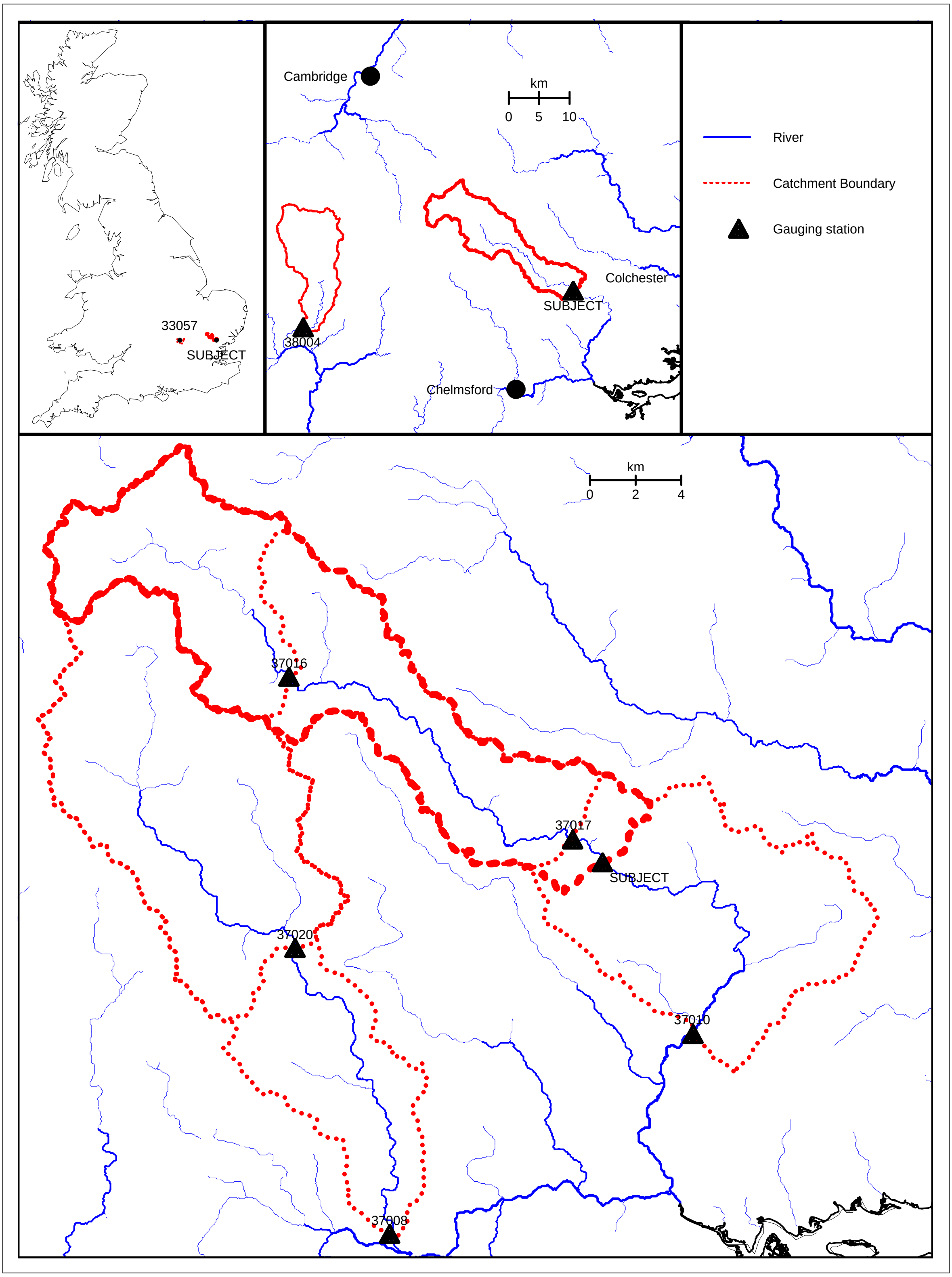


Figure 5.3 Location of target site and all potential donor sites.

Table 5.2 Relevant catchment descriptors (FEH CD-ROM V.2) for the subject site and the potential on- and off-line donor catchments.

National River Flow Archive (NRFA) No.	RIver	Location	Easting (m)	Northing (m)	AREA (km^2)	SAAR (mm)	FARL (-)	BFIHOST (-)
Subject			580550	223300	150.95	578	0.994	0.496
On-line donors								
37016	Pant	Copford Hall	566850	231400	63.77	588	0.997	0.404
37017	Blackwater	Stisted	579250	224300	140.38	579	0.994	0.493
37010	Blackwater	Appleford Bridge	584500	215800	247.09	572	0.992	0.477
Off-line donors								
37008	Chelmer	Springfield	571250	207050	189.65	584	0.985	0.492
37020	Chelmer	Felsted	567100	219550	132.9	588	0.982	0.468
38004	Rib	Wadesmill	536100	217350	136.65	625	0.999	0.469
33057	Ouzel	Leighton Buzzard	491700	224050	122.39	643	0.991	0.524

Table 5.3 Estimation of QMED at the ungauged subject site using both:
i) The FEH data transfer scheme – equation (5.1).
ii) The new data transfer scheme – equation (5.2).

NRFA No.	River	Location	No. of obs	Sample $QMED_{obs}$ (m^3/s)	Model $QMED_{cds}$ (m^3/s)	Distance[1] (km)	Weight[2] a	FEH factor	New factor	FEH $QMED_{adj}$[3] (m^3/s)	New $QMED_{adj}$[4] (m^3/s)
Subject					10.7						
On-line donors											
37016	Pant	Copford Hall	38	8.9	7.1	15.9	0.33	1.26	1.08	13.4	11.5
37017	Blackwater	Stisted	34	13.8	10.2	1.6	0.69	1.36	1.23	14.5	13.2
37010	Blackwater	Appleford Bridge	41	11.3	16.5	8.5	0.40	0.69	0.86	7.3	9.2
Off-line donors											
37008	Chelmer	Springfield	37	14.8	13.1	18.7	0.32	1.13	1.04	12.0	11.1
37020	Chelmer	Felsted	33	13.5	10.5	14.0	0.35	1.28	1.09	13.6	11.6
38004	Rib	Wadesmill	44	12.1	13.8	44.8	0.19	0.88	0.98	9.4	10.4
33057	Ouzel	Leighton Buzzard	22	7.6	11.2	88.9	0.08	0.68	0.97	7.2	10.3

Notes:
[1] Distance between catchment centroids of subject site and donor catchment.
[2] The weight a is defined as $a = r_{sg}$.
[3] Calculated using the FEH data transfer scheme equation (5.1).
[4] Calculated using the new data transfer scheme equation (5.2).

Estimation of QMED at the subject site using the new data transfer scheme requires the calculation of the following quantities.

- Estimates of $QMED_{cds}$ using catchment descriptors at both the subject and the target sites.
- An estimate of $QMED_{obs}$ at the gauged donor site.
- The geographical distance (km) between the centroids of the subject and donor site.

Table 5.3 shows the calculation of the adjusted QMED values for each of the potential donor sites identified in Table 5.2 using both the new and the FEH data transfer methods. Note that the new data transfer method considers only a single donor site at the time.

On comparing the adjusted QMED values ($QMED_{adj}$) obtained using the two different methods, it is clear that the variation between the estimates is smaller for the new method than for the FEH method. This happens because the adjustments to the regression-only estimates are always smaller for the new adjustment method than for the FEH method. These adjustments are shown in Table 5.3 in the columns headed “FEH factor” and “New factor”. The “New factor” is the a’th power of the “FEH factor”, as shown by comparing equations (5.1) and (5.2).

In Table 5.3, one may note that the sample median for The Blackwater at Appleford Bridge is lower than the sample median for Stisted, even though the former is downstream of the latter. It might be thought that this could not be explained by attenuation effects related to flood plains between the two locations. The record lengths are different for the two catchments and this might be a partial explanation. However, examination of the HiFlows-UK records for these catchments indicates that the annual maximum flows for the same years are often such that those for the downstream catchment are lower than those for the upstream catchment, although not consistently. This may warrant further investigation.

6 Improving the FEH pooling procedure

Use of the pooling-group method, as described by Robson and Reed (1999), was introduced in the FEH to overcome the problems often associated with the use of fixed regions such as those used in the FSR. These problems include issues of the regional memberships of catchments located on or near the boundary between two or more regions and the pooling of data that are geographically close but not necessarily similar in terms of hydrology.

A subsequent appraisal of the FEH statistical method carried out by Morris (2003) resulted in valuable feedback and highlighted a number of methodological issues in need of refinement and further research, including the following points.

- Poor performance of the pooling method for certain catchments when compared to at-site data.
- The weighting of L-moment ratios within pooling-groups depends on the rank, rather than directly on distance in catchment descriptor space. By default the rank is the ordering by distance in catchment descriptor space..
- Using a variable size of pooling-group depending on return period can lead to contradictory flood estimates.

In his appraisal, Morris (2003) found that a "*single national growth factor performed better than the default FEH pooling-groups at the 10, 15 and 30-year return periods and almost as well at the 50-year (when tested at gauged locations, with the gauging station excluded from the pooling-group).*"

Other issues regarding the suitability of the pooling-group heterogeneity measure (H_2) and the procedure for adjusting the growth curve for the impact of urbanisation were also discussed by Morris (2003), but are outside the scope of this project. Some have already been addressed: for example, Bayliss *et al.* (2006) presented an improved method for the adjustment of FEH growth curves based on URBEXT_{2000} rather than URBEXT_{1990} as used in the FEH.

The FEH pooling-group method is a hybrid of the index-flood method (Stedinger *et al.*, 1993) combined with the Region of Influence (ROI) approach for formation of pooling-group suggested by Burn (1990) on the basis of work by Acreman and Wiltshire (1987, 1989). The underlying assumption of the index-flood method is that the true distribution of the annual maximum peak flows from the different catchments in a pooling-group are identical, except for a scaling parameter denoted the index flood. By forming pooling-groups based on hydrological similarity, it is assumed that the catchment descriptors used in the distance measure can adequately explain the variability of the growth curves (L-moment ratios) between the catchments. However, by subsequently ordering the catchments within the pooling-group based on their rank (or distance), the method acknowledges that the catchments are in fact not similar, and hence the method departs from the underlying assumptions of the index-flood method. While these considerations might not affect the practical use of the method, they are important when developing the underlying statistical framework necessary for optimising the performance of the pooling-group method. The development of the method needs to consider the following aspects.

- Formation of pooling-groups.
- Weights within pooling-groups.

- Size of pooling-group.
- Performance of method.

These four aspects of the method are highly inter-dependent and ideally should be considered simultaneously. However, it was necessary to adopt a more sequential approach for practical reasons. Each of the first three aspects were analysed in turn and, once a decision was made, the next aspect was considered. While the reporting might give the impression of a straightforward process, in practice the analysis was very exploratory and each aspect was re-investigated several times to assess the effects of changes related to the other aspects.

6.1 Pooled frequency analysis

The FEH recommends the three-parameter Generalised Logistic (GLO) distribution for flood frequency analysis in the UK. The quantile function or inverse of the cumulative distribution function for estimating the T-year event, x_T, is given as

$$x_T = \xi + \frac{\alpha}{\kappa}\left(1-(T-1)^{-\kappa}\right) = \xi\left[1+\frac{\beta}{\kappa}\left(1-(T-1)^{-\kappa}\right)\right] = \xi\, z_T\,, \tag{6.1}$$

where ξ, α, and κ are GLO model parameters, T is the return period and z_T is the growth curve at T defined by the square brackets in equation (6.1). The parameter estimation method used in this study is the method adopted by the FEH (Institute of Hydrology, 1999) and is a variant of the method of L-moments described by Hosking and Wallis (1997). Given a flow series from a particular gauging station with a series of *n* annual maximum peak flow values, the location parameter, ξ, is estimated by equating the distribution median to the sample median

$$\hat{\xi} = median(x_1,\ldots,x_n), \tag{6.2}$$

which is given more explicitly in equation (4.1).

Next, the shape parameter, κ, and the rescaled scale parameter, $\beta = \alpha/\xi$, are estimated as

$$\begin{aligned}\hat{\kappa} &= -t_3,\\ \hat{\beta} &= \frac{t_2\hat{\kappa}\sin(\pi\hat{\kappa})}{\hat{\kappa}\pi(\hat{\kappa}+t_2)-t_2\sin(\pi\hat{\kappa})},\end{aligned} \tag{6.3}$$

where t_2 and t_3 are the sample L-moment ratios L-CV and L-SKEW, respectively, as defined by Hosking and Wallis (1997).

When extending the at-site analysis to a pooled frequency analysis, the FEH uses the median-based index-flood method. This means that the T-year event is estimated as

$$x_T^P = \xi\, z_T^P\,, \tag{6.4}$$

which has a similar structure to the at-site case in equation (6.1), but the superscript P indicates that the factors are obtained from a pooled analysis. The pooled growth curve z_T^P is estimated using information from M sites in the pooling-group that are deemed sufficiently hydrologically similar to the catchment of interest. The parameters of the pooled growth curve are estimated by substituting the pooled L-moment ratios, t_2^P and t_3^P, into equation (6.3). The pooled L-moment ratios themselves are calculated as the weighted average of the individual at-site L-moment ratios within the pooling-group.

Thus, for a pooling-group consisting of M catchments, the pooled L-moment ratios are given as

$$t_r^p = \sum_{i=1}^{M} \omega_{r,i} t_{r,i} \tag{6.5}$$

where $\omega_{r,i}$ are the weights assigned to the i'th catchment for L-CV (r = 2) or L-SKEW (r = 3).

The FEH recommended a set of weights based on rank within the pooling-group and record length, and the same weights were used for both L-moment ratios. In the following, new sets of improved weights will be derived based on a statistical model for the underlying statistical structure of the pooling-groups.

6.2 Performance measure

To assess the performance of alternative pooling procedures, the FEH developed a pooled uncertainty measure (PUM) defined as

$$PUM_T = \left(\frac{\sum_{i=1}^{M} w_i \left(\ln x_{T_i} - \ln x_{T_i}^p \right)^2}{\sum_{i=1}^{M} w_i} \right)^{\frac{1}{2}}, \tag{6.6}$$

where x_T is the at-site and x_T^p is the pooled T-year growth factor, and w_i is the weight assigned to the i'th catchment. The at-site values of the growth factor are obtained from a GLO distribution fitted by L-moments.

The rationale behind the PUM measure is that a good pooling method will, on average, produce growth curves that are close to the true growth curves for the site of interest where the true growth factor in this study is defined as the at-site growth factor. Two minor changes to the FEH-PUM measure have been adopted in this study. Firstly, the FEH considered only catchments with a record length exceeding 20 years whereas in this study no such censoring of the dataset was applied and all catchments were used. Secondly, the FEH defined the weights to be equal to record length. However, it was found that using record length gave too much weight to a few catchments with long record length. The present study has used a new set of weights were defined as

$$w_i = \frac{n_i}{1 + n_i / 16}, \tag{6.7}$$

where n_i is the record length. This has the effect of reducing the importance assigned to individual catchments with long records, while still giving average and long records more importance than very short records.

The weights in equation (6.7) were selected on the basis of simulation experiments which compared the between-site variation of at-site estimates of the growth curves with the sampling errors in these estimates for different record lengths. Some statistical theory indicates how these results can be used to derive an "optimal" weighting scheme. Somewhat different weights would notionally be required for the growth-curves (and hence for the PUM measure) for different return periods. The divisor "16" in equation (6.7) is a compromise that should be suitable for all return periods. Preference is given here to having simple, understandable weights rather than to an "optimality" that relies on an inadequate model.

6.3 Formation of pooling-groups

As in the FEH, this study has adopted the ROI approach for creating pooling-groups tailored to each specific site of interest. By considering catchments which are similar to the site of interest (gauged or ungauged) with regard to a chosen set of catchment descriptors, it is assumed that these catchments are also ‘hydrologically similar’. The term ‘hydrologically similar’ means that a particular site does not violate the fundamental assumption of the index-flood method, i.e. that the AMAX flood series is generated from an underlying flood distribution with high order moments (L-CV and L-SKEW) equal to those at the subject site. The FEH adopted a similarity distance measure (*SDM*) to judge the similarity between catchment pairs. The catchment descriptors defining the *SDM* are called the pooling variables and the *SDM* itself is defined as

$$SDM_{ij} = \sqrt{\sum_{k=1}^{n} \omega_k \left(\frac{x_{i,k} - x_{j,k}}{\sigma_k} \right)^2} , \qquad (6.8)$$

where $x_{i,k}$ is the *k*’th pooling variable at the *i*’th catchment, ω_k is the weight assigned to the *k*’th pooling variable, and σ_k is the standard deviation between sites of the *k*’th catchment descriptor. Morris (2003) found that varying the weights in the FEH SDM had little effect on the overall performance of the pooling method.

6.3.1 Selecting variables for formation of pooling-groups

Linear regression models describing the L-moment ratios (L-CV and L-SKEW) as a function of catchment descriptors were used to identify potential combinations of catchment descriptors to be used in the formation of pooling-groups, i.e. to define hydrological similarity. A comprehensive search was conducted to identify the optimal combinations of catchment descriptors when using from one to ten different descriptors. Both log-transformed and non-transformed versions of the catchment descriptors were included in the search. The L-moment ratios themselves were not log-transformed in this experiment.

A similar investigation was conducted as part of the FEH development (Vol.3, §16.4.2) where it was found that 37.5 per cent and 8 per cent of the between catchment variation of L-CV and L-SKEW, respectively, could be explained using a regression model. These relatively low r^2 values are in stark contrast to the 94 per cent of explained variance for the index flood (QMED) and might help to understand why discrepancies between at-site growth curves and the corresponding growth curves obtained using the pooling-group method can occur. For QMED, the descriptors AREA and SAAR have a strong explanatory power, while there are no such useful descriptors for L-CV or L-SKEW. This is partly because L-CV or L-SKEW are both standardised variables. The effects of sampling error are relatively greater for L-CV, L-SKEW and for at-site growth curves than for QMED.

The FEH based the formation of pooling-groups on three catchment descriptors (ln[AREA], ln[SAAR] and BFIHOST) which were selected on the basis of the preliminary regression analysis. It was noted that regression models using a larger number of descriptors performed only marginally better.

Possible catchment descriptors for L-CV

The FEH Vol.3 (16.4.2) found that 37.5 per cent of the variation in sample L-CV values could be explained by a log-linear regression model based on ln[AREA], ln[SAAR], BFIHOST, ln[CVRI] and the seasonality vector (XFLOOD, YFLOOD). In this study, the optimal regression model based on four descriptors uses ln[AREA], ln[SAAR], FARL and 1-FPEXT. While the first two descriptors are consistently being selected in the optimal model, there is some suggestion that the log-transformed versions of FARL and 1-FPEXT might also be useful candidates. This suggests there may be some minor benefit in a fuller consideration of other non-linear transformations of these variables. Other potential descriptors selected are generally highly correlated with ln[SAAR] and have therefore not been selected. A minimum of 10 other variables were selected before BFIHOST, which contrasts strongly with the findings of the FEH.

Possible catchment descriptors for L-SKEW

The FEH Vol.3 (16.4.2) found that only 8 per cent of the variation in sample L-SKEW values could be explained by a log-linear regression model based on ln[AREA] and ln[NWET]. Clearly, the relationship between sample values of L-SKEW and the catchment descriptors is less significant than for L-CV. The optimal four-parameter regression model describing L-SKEW included: ln[AREA], ln[SAAR], 1-FPEXT and AREA (untransformed). The FARL descriptor did not appear to be strongly linked to L-SKEW. Furthermore, as for L-CV, BFIHOST also appears not to be a controlling factor for L-SKEW.

6.3.2 Final distance measure

The regression models selected for L-CV and L-SKEW share three catchment descriptors: ln[AREA], ln[SAAR] and 1-FPEXT. Based on the strong links between FARL and L-CV, it was decided to include FARL with the three other catchment descriptors in a single distance measure to be used to select a single pooling-group to be used for both L-moment ratios.

In the FEH, the weights assigned to each of the three catchment descriptors in the *SDM* measure was initially set to unity, but later the weight assigned to ln[AREA] was changed to 0.5 as this descriptor was found to exert "*too large an influence on the final selection of site*" (Institute of Hydrology, 1999) without further specifying the exact meaning of this. In this study, the weight assigned to each of the four catchment descriptors (ln[AREA], ln[SAAR], FARL and FPEXT) was investigated through an empirical procedure and was based on PUM values calculated from the data-set.

At this stage in the procedure, the set of weights used within each pooling-group to calculate the pooled L-moment ratios have not yet been defined. Instead, the L-moment ratio (either L-CV or L-SKEW) for each catchment is weighted according to its record length as shown in equation (6.7). The first step in the procedure is to set all four weights in the *SDM* to unity. Next, the weight assigned to the first catchment descriptor was set to vary between zero and ten (step 0.25). For each combination of weights, pooling-groups containing 17 catchments were formed for each of the 602 catchments and the resulting PUM calculated. Re-scaling of each of the trial set of weights was undertaken to ensure that the weights in the *SDM* measure sum up to four (the same as unity weights). Note that 17 catchments were used as a reasonable first guess of pooling-group size at this stage in the procedure.

Having identified an optimal, or near-optimal, value of the weight of ln[AREA], the weight of the second catchment descriptor, ln[SAAR], was set to vary between zero and ten, with unity weight on FARL and FPEXT but with the weight on ln[AREA] changed from unity to the optimal weight identified in the previous step. As before, the optimal weight of ln[SAAR] is noted, and the procedure then moves on to FARL and finally FPEXT. The results obtained from the procedure are illustrated in Figure 6.1. For each catchment descriptor the final weight is set to the value that results in the minimum PUM value. It was found that only one run through the procedure was necessary to obtain a stable set of weights.

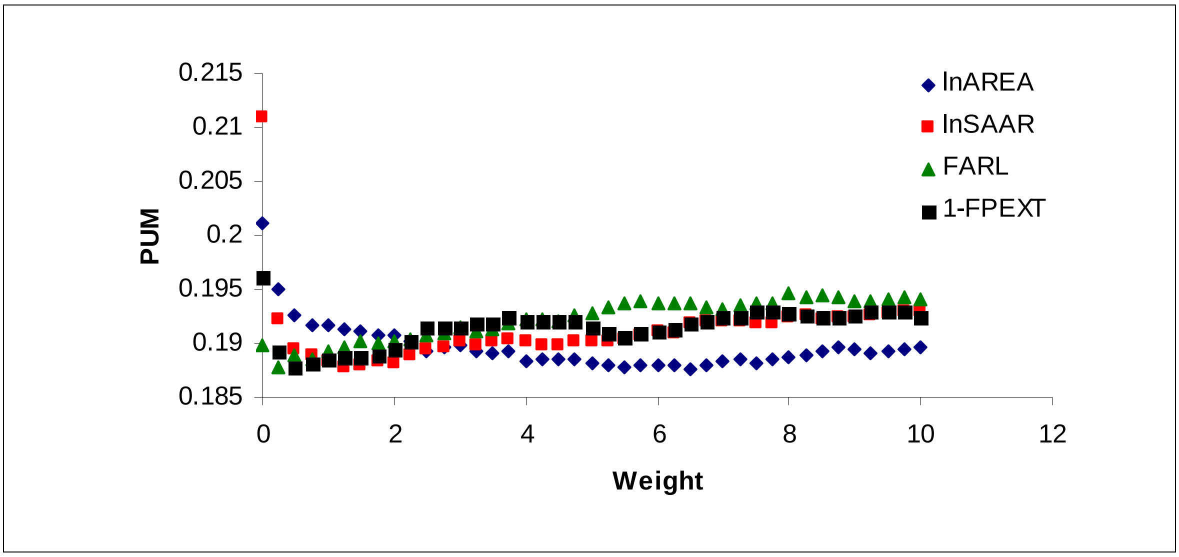


Figure 6.1 PUM values for different combinations of weights in the SDM measure as determined by the empirical procedure. Note that the weights on the x-axis represent the unscaled weights.

The final unscaled weights are obtained from the analysis in Figure 6.1 and are as follows: ln[AREA] (7.0), ln[SAAR] (1.25), FARL (0.25) and FPEXT (0.50). For ln[AREA] the weights were relatively insensitive for values between 5 and 8, and finally a value of 7 was chosen. These weights were subsequently scaled to ensure that they sum to four and the final *SDM* measure is shown below:

$$SDM_{ij} = \sqrt{3.2\left(\frac{\ln AREA_i - \ln AREA_j}{1.28}\right)^2 + 0.5\left(\frac{\ln SAAR_i - \ln SAAR_j}{0.37}\right)^2 + 0.1\left(\frac{FARL_i - FARL_j}{0.05}\right)^2} \\ \overline{+0.2\left(\frac{FPEXT_i - FPEXT_j}{0.04}\right)^2}. \qquad (6.9)$$

In Figure 6.1 it can be observed that the effect of leaving out any of the catchment descriptors (setting the weight to zero) results in a substantially higher value of PUM, except for FARL. This suggests that FARL is the least important catchment descriptor in the distance measure.

6.4 Weight of L-moments within pooling-groups

A method for assigning weights to individual members of a pooling-group based on record length and rank was developed as part of the FEH statistical method. In a part of his study which concentrated mainly on the spatial coherence of the estimates obtained as part of an automated procedure, Morris (2003) identified the following problems with the FEH weighting scheme.

- It depends on rank.

- The weights do not diminish gradually to zero down the ranked list of catchments by the point at which they leave the pooling-group.
- Use of record length in the weights results in undesirably high weights being assigned to low ranking sites with relatively long records.

The study then went on to suggest replacing the rank-based FEH weights with a set based on a distance in catchment descriptor space between the site of interest and individual sites in the pooling-group.

When developing a revised weighting scheme in this project, a number of issues were considered. Firstly, the idea put forward by Morris (2003) that the weighting should depend on distance in catchment descriptor space has been adopted, but in a modified form. Secondly, the revised weighting scheme makes a distinction between pooling-groups for gauged and ungauged sites. Where the existing FEH weighting scheme can only include the available at-site data by assigning the first rank position to the site of interest, the new methodology assigns relatively more importance to at-site data than data from other catchments in the pooling-group. Finally, a new set of weights is developed separately for L-CV and L-SKEW, although only one pooling-group will be created for each site of interest.

In Section 6.4.1 the structure of the new weighting scheme is outlined and the associated parameters for use with the weighting scheme will be estimated in Section 6.4.2. The statistical model forming the basis of the weighting scheme is described in detail in Appendix D.

6.4.1 New weighting scheme

Based on the discussion above and in Appendix D, the suggested form of the weighting for a particular L-moment ratio was defined as

$$\omega_i \propto \left(\alpha + c_i + f\left(SDM_i \middle| \boldsymbol{\beta}\right)\right)^{-1}, \quad i = 1,\ldots, M, \qquad (6.10)$$

where c_i is the sampling variance of the L-moment ratio for the i'th site , M is the total number of sites in the pooling-group and SDM_i is the distance in catchment descriptor space between the subject site and the i'th site (specifically this is the similarity distance measure (*SDM*) of Section 6.3).

The sum $\alpha + f\left(SDM_i \middle| \boldsymbol{\beta}\right)$ in equation (6.10) represents the variance of the structural error. This error represents the uncertainty arising because the true values of the L-moment ratios for each site in the pooling-group are different from the corresponding true value at the subject site. There is an assumption that these differences tend to grow with an increase in the distance in the catchment property space (SDM_i) between the subject catchment and the i'th catchment and this is the role of the term f in the sum. The vector $\boldsymbol{\beta}$ contains a set of model parameters for f that need to be estimated.

It is necessary to distinguish the roles of α and f within the model, which can be done by imposing the constraint that $f\left(0 \middle| \boldsymbol{\beta}\right) = 0$. This means that the term α represents the effect of differences between the true L-moment ratios for catchments at a distance of zero in catchment descriptor space ($SDM_i = 0$). That is, if two catchments had exactly the same values for the four catchment descriptors defining SDM, they would still not be expected to have exactly the same true underlying values for their L-moment ratios. Next, the term f represents the effect of the extra difference to be expected for more dissimilar catchments (i.e. larger SDM values). When catchments in the pooling-group become increasingly different from the subject catchment (as measured by the catchment properties), the values of f will become larger and the weights determined from equation (6.10) will be smaller. Correspondingly, if the record length available at a catchment in the pooling-group is relatively short, then the sampling variance of the L-moment ratios, c_i, will be relatively large and hence the weight will be small.

Both the functional form of f and its associated parameter vector $\boldsymbol{\beta}$ need to be estimated based on analysis of the observed data, which is reported in Section 6.4.2, and this also leads to the estimation of α. For convenience, the following notation is defined for use in the weighting scheme:

$$b_i = \alpha + f\left(SDM_i \middle| \boldsymbol{\beta}\right). \tag{6.11}$$

Before estimating the model parameters, the structure of the new weighting scheme is introduced. The weight assigned to each site in the pooling-group depends on whether the subject site is gauged or ungauged. The two cases are presented separately.

No information at subject catchment (ungauged)

The weighted average L-moment ratio is calculated as

$$t_r^p = \sum_{i=1}^{M} \omega_{r,i} t_{r,i} \tag{6.12}$$

for a set of weights $\omega_{r,i}$ which sum up to one, and where $t_{r,i}$ is the L-CV (r = 2) or L-SKEW (r = 3) for the i'th catchment in the pooling-group. For the ungauged catchment, the weights are defined as

$$\omega_j = \frac{\left\{c_j + b_j\right\}^{-1}}{\sum_{k=1}^{M} \left\{c_k + b_k\right\}^{-1}}, \tag{6.13}$$

where different sets of coefficients c_j and b_j for the two L-moment ratios give two different sets of weights ω_j.

Estimation of the model parameters is outlined in Section 6.4.2.

Data available at the subject catchment (gauged)

When data are available at the subject catchment it is considered in the form of an observed value of the L-moment ratio, t_r, which has a sampling error variance as a result of being estimated from a data series of limited extent. As for the ungauged case, the weighted average L-moment ratios are calculated as

$$t_r^p = \sum_{i=1}^{M} \omega_{r,i} t_{r,i}, \tag{6.14}$$

using a set of weights $\omega_{r,i}$ which sum up to one, and where $t_{r,i}$ is the L-CV (r = 2) or L-SKEW (r = 3) for the i'th catchment in the pooling-group. As the observed data at the subject catchment are considered more important than information at other catchments in the pooling-group, a set of weights have been defined reflecting this distinction. Thus the weights are

$$\omega_1=\frac{b_1}{c_1+b_1}+\frac{c_1\left\{c_1+b_1\right\}^{-2}}{\sum_{k=1}^{M}\left\{c_k+b_k\right\}^{-1}}\ , \tag{6.15a}$$

$$\omega_j=\frac{c_1\left\{c_1+b_1\right\}^{-1}\left\{c_j+b_j\right\}^{-1}}{\sum_{k=1}^{M}\left\{c_k+b_k\right\}^{-1}}\qquad j=2,\cdots,M\ , \tag{6.15b}$$

where it is assumed that the subject catchment has subscript 1 in the list of catchments in the pooling-group.

The actual model parameters, which are used for both the gauged and ungauged cases, are estimated in Section 6.4.2. Specifically, these are α and $\boldsymbol{\beta}$, which determine b_j via equation (6.11). The other quantities c_j are the sampling variance of the L-moment ratios and are specified in Section 6.4.2 via equations (6.18) and (6.19).

6.4.2 Estimation of model parameters

An initial attempt to estimate the parameter α and a linear form of the function f in equation (6.11) by minimising the PUM score was unsuccessful due to the relative insensitivity of the PUM scores to those model parameters. As an alternative, the parameters were estimated based on a variogram analysis. The linkage between the weights and the variogram is complex and derived through consideration of the structure of the statistical errors involved in the estimation of the pooled L-moment ratios: see Appendix D. The key-result is that the points in a sample variogram, γ, should cluster around a line defined as

$$\gamma(s)=2\alpha+f\left(s|\beta\right), \tag{6.16}$$

where raw estimates of this function can be obtained for distances $s = SDM_{ij}$, and where SDM_{ij}, is the distance in catchment descriptor space between catchments i and j as defined in equation (6.9) (for a complete description please refer to Appendix D). By noting the similarity between the function defining the weights in equations (6.11) and (6.16) above, it is possible to derive a set of weights for both L-CV and L-SKEW based on a set of models fitted to sample variograms of the L-CV and L-SKEW sample values. Equation (6.16) represents the theoretical variogram of the true L-moment ratios. A raw estimate of the variogram would be affected by terms related to the variogram of the sampling errors and a correction is therefore necessary. In addition, sampling errors in the raw estimates are reduced by averaging over a number of pairs of catchments that are approximately the same distance apart. The corrected and smoothed variogram estimator is given, for r = 2,3, by

$$\hat{\gamma}_r(s)=\frac{1}{\left|n(s,\Delta s)\right|}\sum_{n(s,\Delta s)}\left\{\left(t_{r,i}-t_{r,j}\right)^2-\left(c_i+c_j-2\frac{n_{ij}}{\sqrt{n_i n_j}}\sqrt{c_i c_j}\,\mathrm{cor}\left\{t_{r,i},t_{r,j}\right\}\right)\right\}\ , \tag{6.17}$$

where the set $n(s,\Delta s)$ consists of the catchment pairs (i,j) for which the distance SDM_{ij} is between $s-½\Delta s$ and $s+½\Delta s$, c_i is the sample variance of the r'th L-moment ratio ($t_{r,i}$) for catchment i which has record length n_i, and n_{ij} is the number of overlapping years between catchments i and j. Here the distance SDM_{ij} is measured in catchment descriptor space using equation (6.9). The notation $\left|n(s,\Delta s)\right|$ denotes the number of pairs in the set $n(s,\Delta s)$.

The sampling variance, c_j, of the higher order L-moment ratios can be estimated using different methods. Kjeldsen and Jones (2004) developed a set of approximate analytical estimators, but they were considered too complex to be of practical use in this study, especially as part of the weighting scheme in equations (6.12) to (6.15). As an alternative, a set of simple approximations were developed based on Monte Carlo simulations from a "typical" GLO distribution, selected as representative of the whole of the UK. This study related the sampling variance of L-CV and of L-SKEW to record length only, and gave the following results:

L-CV $$c_k = \frac{0.02609}{n_k - 1} \qquad (6.18)$$

L-SKEW $$c_k = \frac{0.2743}{n_k - 2} \qquad (6.19)$$

Notionally, these sampling variances should vary with the parameters of the distribution appropriate for any given site, but the use of the "average" values should be adequate for the purpose of defining the weights used to calculate the estimated L-moment ratio for a pooling-group.

The correlation of the sample L-moment ratios between sites was obtained through a bootstrapping experiment and defined as a function of geographical distance between catchment centroids:

L-CV $$cor\left\{t_{2,i}, t_{2,j}\right\} = \exp\left(-0.030 d_{ij}\right) \qquad (6.20a)$$

L-SKEW $$cor\left\{t_{3,i}, t_{3,j}\right\} = \exp\left(-0.050 d_{ij}\right) \qquad (6.20b)$$

where d_{ij} is distance between catchment centroids in kilometres. The structure of the bootstrapping experiment was similar to that used in Section 4.3 for estimating the correlation of the log-transformed QMED values between sites.

Information concerning typical distances in catchment descriptor space observed in a pooling-group is required in order to define appropriate values of $s=SDM$ and the total number of bins for which the variogram is defined. Table 6.1 shows the average and maximum distance observed when a pooling-group consisting of 30 catchments was defined for each of the 602 catchments used in this study.

Table 6.1 Typical values for distances in catchment descriptor space observed for 602 pooling-groups consisting of 30 catchments each.

	Distance
Average distance within pooling-groups	0.64
Average maximum distance within pooling-groups	0.85
Maximum average distance within pooling-groups	3.46
Maximum observed distance between any two catchments	11.04

Based on the distances in Table 6.1, it was decided that the maximum distance within any pooling-group would usually be below 4.0. Based on a number of trials, the number of distance-intervals, the number of different $n(s, \Delta s)$ sets, was set to 100. Estimates of the variograms for L-CV and L-SKEW obtained using equation (6.17) are shown in Figure 6.2. The shape of the plots indicated that a functional relationship could be fitted, linking the variogram to the distance, using an empirical type function that was found to fit the data reasonably well:

$$\gamma(s) = \left(\beta_1\sqrt{s} + \beta_2\right)\left(1 - \exp\left[-\frac{s}{\beta_3}\right]\right)^{\delta} \tag{6.21}$$

where $\boldsymbol{\beta}^T = (\beta_1, \beta_2, \beta_3)$ are model parameters and δ is a binary parameter that can be either 1 or 0, depending on whether the variogram has a nugget at distance zero (δ=0) or not (δ=1) . When using equation (6.21) for defining the parameters in equation (6.11), it should be noted that if a nugget exists then $2\alpha = \beta_2$.

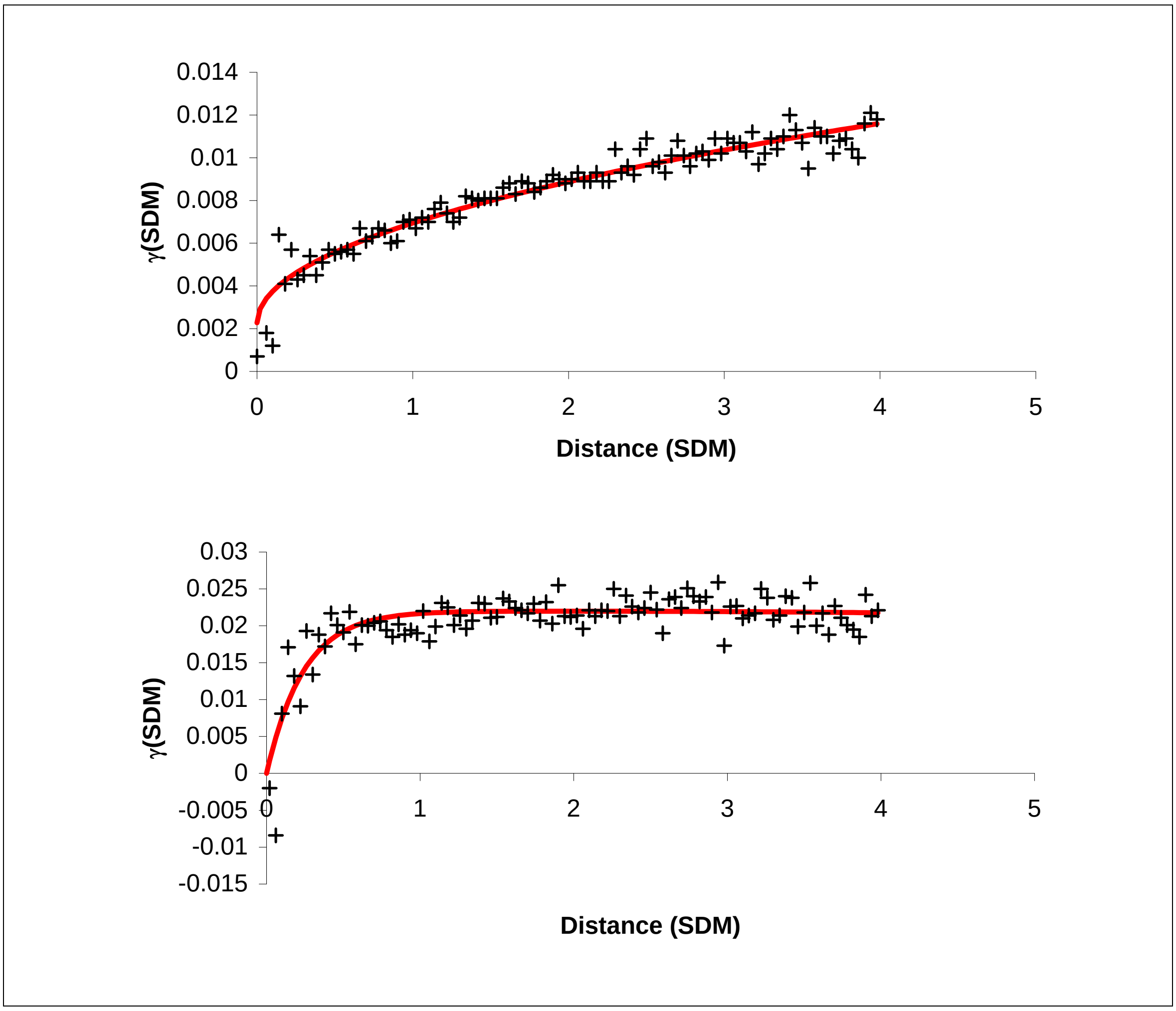


Figure 6.2 Variograms for L-CV (top) and L-SKEW (bottom) plotted as a function of distance in catchment descriptor space. Maximum distance is set to 4 and subdivided into 100 intervals.

Table 6.2 Model parameters for variograms as defined in Equation (6.21)

Model parameter	L-CV	L-SKEW
β_1	0.0047	0.000
β_2	0.0023	0.0219
β_3	n/a	0.2360
δ	0	1

The three parameters $(\beta_1, \beta_2, \beta_3)$ controlling the variograms were estimated based on a least squares analysis. The resulting model parameters are shown in Table 6.2.

In terms of the weighting of the L-moment ratios within each pooling-group, the weighting parameters b_j for L-CV and L-SKEW are defined as

L_CV $$b_j = \left(0.0047\sqrt{SDM_j} + \frac{0.0023}{2} \right) \tag{6.22a}$$

L-SKEW $$b_j = 0.0219\left(1 - \exp\left[-\frac{SDM_j}{0.2360} \right] \right) \tag{6.22b}$$

where SDM_j is the distance in catchment descriptor space from the subject site to the j'th site in the pooling-group. Note that while a nugget effect was observed in the sample variogram for L-CV, no such effect was detected for L-SKEW.

Equations (6.22a and b) are combined with the equations (6.18-9) to give the weights in the two cases of gauged or ungauged catchments (equations (6.13) and (6.15)), from which the pooled L-moment ratios can be derived through equation (6.5).

The variogram functions and the weighting scheme derived from them are considered fairly reliable in terms of stability across other choices that might have been made concerning the functional form of the variogram (including the decision whether to have a nugget effect or not), and also in terms of the range of distances over which the function is fitted. Appendix D outlines the relation between the variogram and the weights Examination of this will show that this link might be regarded as somewhat tenuous. The context here is that we are seeking to respond to FEH-users' comments that the weights given to catchments in a pooling-group procedure should be related to the measure of hydrological similarity between catchments (*SDM* here). The present analysis has used the available data to suggest both what form this relationship should take and to what extent the weights should vary with *SDM*. The variation of the weights is illustrated later in Section 6.7.

6.5 Size of pooling-groups

The final step in the development of the pooling procedure is to determine the number of catchments to be included in a pooling-group. The best size of a pooling-group is a trade-off between the bias (precision) and variance (uncertainty) of the estimated T-year flow. Too many sites in a pooling-group will increase the possibility of including sites that are markedly different from the target site, thereby increasing the bias of the T-year event. On the other hand, including too few sites will lead to estimates with a larger variance (higher uncertainty) for the T-year estimate than necessary. Based on a series of Monte Carlo experiments, Hosking and Wallis (1997) found that little could be gained, in terms of RMSE, by using regions larger than about 20 sites.

Within the context of a pooling-group procedure such as that recommended in the FEH, the size of the pooling-group used has implications for the amount of effort that would need to be expended by a "User", since the records for catchments in the pooling-group should be brought up to date and checked. Fortunately, the size of pooling-groups that appear to be best on other grounds do not seem to lead to too onerous a task for the user.

The size of a pooling-group can be quantified either in terms of the number of sites or the total number of AMAX events. The FEH opted for the latter measure because of the large variation in record length observed in practice. While not eradicated, this problem might be less severe when using the updated HiFlows-UK dataset where the average record length is approximately 10 years longer than the original FEH data set.

The FEH introduced a 5T rule, allowing the size of the pooling-group to be determined by the target return period. For example, for a target return period of T = 100 years, sites should be added to the pooling-group until 500 AMAX events has been reached. However, the FEH stated that this was indeed a ‘rule-of-thumb’, and based on intuition rather than the outcome of a particular analysis. Later, Morris (2003) found that varying pooling-group size according to the 5T rule could lead to contradictory flood estimates and cites an example where a 200-year flood is estimated as being smaller that the 10-year flood. As a result, Morris (2003) recommended using a single pooling-group size for all return periods, and used a total number of AMAX events corresponding to a 200-year target return period, i.e. 1,000 AMAX events.

In this study, the size of the pooling-group was investigated in terms of both the number of catchments and the number of AMAX events. In each case the PUM criterion (equation (6.6)) was used to assess the appropriate size. Figure 6.3 shows how the PUM criterion varies according to size for both cases.

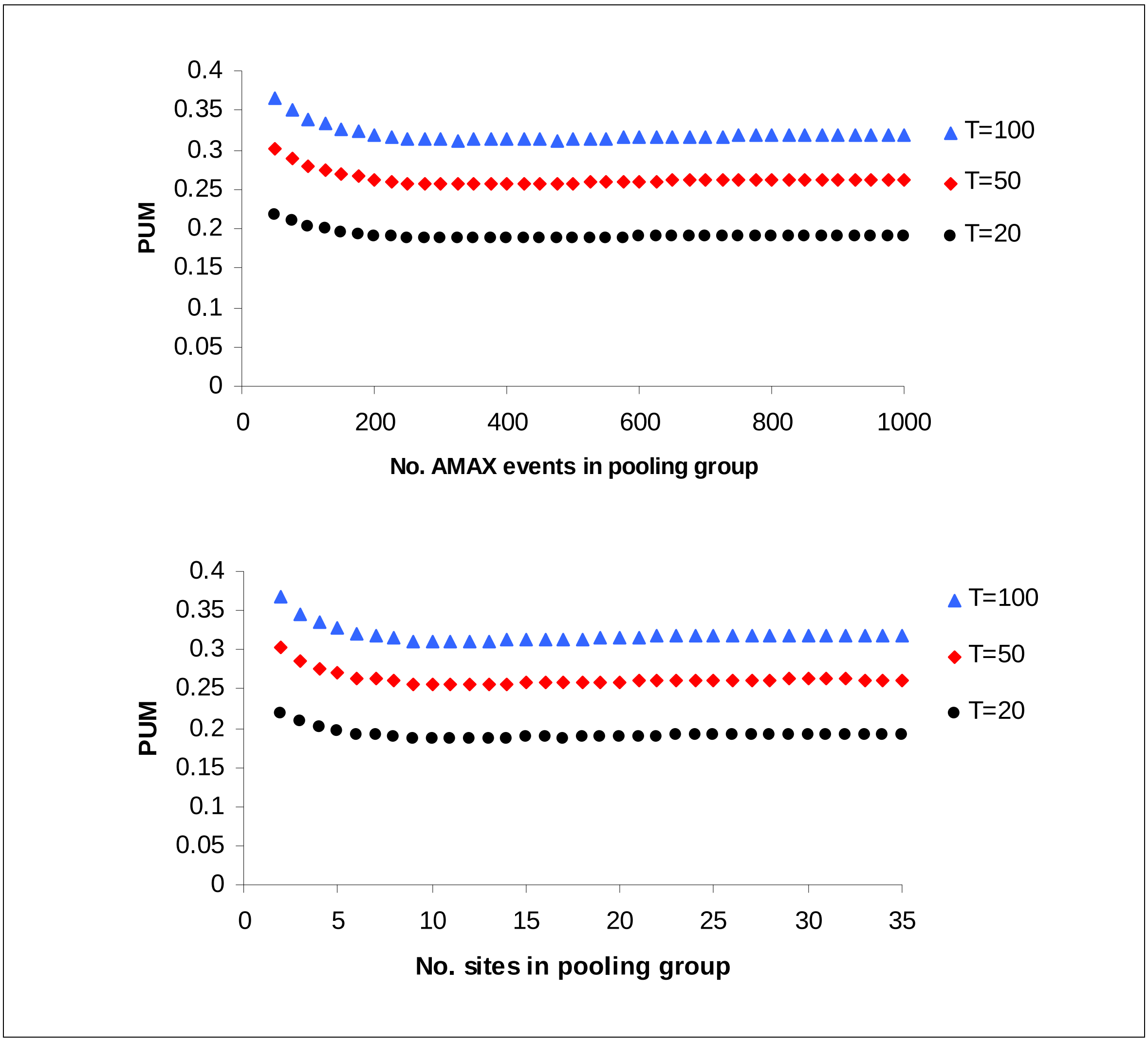


Figure 6.3 PUM as a function of pooling-group size measured by a) number of AMAX events and b) number of sites. PUM was calculated for both T=20, T=50, and T=100.

For both measures of pooling-group size, the PUM decreases rapidly from high values for very small pooling-groups until a size of 10 sites (or about 300 AMAX events) is reached. Between 10 and 17 sites (or between 300 and 500 AMAX events) little change in PUM can be observed. After this point the PUM rises slowly for increasing pooling-group size. There is no evidence from the data analysed in this study that the pattern described above changes as a function of target return period. Based on these results, there seems to be no reason why one method of measuring pooling-group size should be preferred over another. It is therefore recommended that the current measure used in the FEH be retained, that is, to go on using the number of AMAX events.

With regard to the actual size of the pooling-groups, the current FEH practice recommends using the 5T rule, but the results reported here support the recommendation made by Morris (2003) that a single pooling-group size should be applied irrespective of the target return period. The results shown in Figure 6.3 suggest little effect on the PUM measure if pooling-groups are based on between 300 and 500 AMAX events. Consequently, using a default pooling-group size of 500 AMAX events is recommended for all return periods, which corresponds to the size of a pooling-group for a 100-year target return period under the current FEH guidelines.

6.6 Performance of pooling-groups

The performance of the pooling-group method needs to be assessed for two different cases. Firstly, performance is assessed for the case of the ungauged site where no at-site data are available, and, secondly, for the gauged site, where the performance should be compared to the results obtained from a standard single-site flood frequency analysis. The methods used for assessing the two cases are very different and will be reported separately in the following.

6.6.1 The ungauged site

The pooling-group method derived in the previous sections is only one candidate out of many possible procedures that could have been specified. At each step in the development a range of different options could have been selected, which would have led to a modified end-product. However, the development should be reasonably close to an optimal procedure (with regards to PUM), as each step in the development was justified through careful analysis of the data. To provide further evidence of the improvements made during this project, the new method developed here is compared to the following series of alternatives.

- A simplified procedure (simple weights).
- A single UK growth factor.
- Pooling-groups based on geographical distance only.
- The FEH methodology.
- Weighted Least Squares (WLS) regression models for L-CV and L-SKEW.

Here the simple weights are defined using equation (6.7). The single UK growth factor is obtained by using the weighted average L-moment ratios, averaged for the whole of the UK. For the final option listed, the regression models are the models for L-CV and L-SKEW that are reported in Section 6.3.1, where they are used to help select the descriptors to be used in measuring the similarity between catchment: a weighted least squares (WLS) fit is used.

Table 6.3 Comparison of pooling methods using PUM.

		T = 20	T = 50	T = 100
1	New method	0.1875	0.2576	0.3134
2	New method, simple weights	0.1886	0.2591	0.3152
3	Single UK growth curve	0.2164	0.2914	0.3501
4	Geographical proximity[1]	0.1926	0.2651	0.3226
5	FEH method[2]	0.1986	0.2718	0.3296
6	Regression models	0.1881	0.2598	0.3170
7	New method, gauged site	0.1095	0.1622	0.2062

Notes: [1] Pooling-group size of 700 AMAX events.
[2] Pooling-group size of 500 AMAX events.

Each of the alternatives listed above has been assessed using the PUM measure by considering each of the 602 catchments, in turn, to be ungauged (i.e. the subject site is excluded from its own pooling-group), and calculating PUM for return periods of 20, 50 and 100 years. The results are summarised in Table 6.3. From this table, it is clear that the new method performs better than the existing FEH methodology. The FEH methodology included i) defining pooling-groups based on hydrological similarity as defined in the FEH (ln[AREA], ln[SAAR] and BFIHOST), and ii) calculating the weight of the individual L-moment ratios using the FEH weighting scheme (i.e. based on rank and record length). However, the analysis was based on the 602 AMAX series from HiFlows-UK data used in this study rather than the FEH dataset.

It is worth noting that the increase in performance gained by introducing the new weighting scheme is rather small compared to the method using relatively simple weights given by equation (6.7). However, the more complicated new weighting scheme is recommended as it includes an effect whereby the weights given to catchments in the pooling-group tend to decrease as the catchments become less hydrologically-similar to the subject catchment. This has previously been considered an important requirement by users commenting on the existing FEH pooling-group scheme.

The regression approach also produces competitive results. In fact, there is still some scope for improvement here since a full consideration of alternative transformations of the descriptors has not been undertaken -- specifically, the type of consideration reported in Section 4.4.3 for the QMED regressions, which led to an improved predictor of QMED.

Implementation of a regression-based approach would replace the pooling-group approach to estimating L-CV and L-SKEW with simple equations for these. There would be the possibility of extending these by adding a donor-catchment adjustment similar to that for QMED. Even if the regression approach could be improved, there is a good reason to retain the pooling-group approach in preference to it. Specifically, the pooling-group approach allows the User to incorporate up-to-date information from relevant sites without having to carry out a full investigation of all sites in the country.

6.6.2 The gauged site

At the gauged site the benefit of using pooled analysis should be compared to a direct at-site analysis of the available data, and should ideally consider aspects of variability and bias of the estimated design events. Based on a series of Monte Carlo experiments, Hosking and Wallis (1997) concluded that while pooled (or regional) analysis might be considered beneficial for a region overall, at-site analysis might still be preferable at individual sites. The design of a suitable Monte Carlo experiment considering the whole of the UK was considered outside the scope of the current project. Instead, a more direct comparison was made based on the PUM criterion.

It can be argued that the PUM criterion is not suitable for a comparison of at-site and pooling procedures in the “gauged case”, as it will favour any pooling procedure giving results close to the at-site results without consideration of variability of the estimates. In particular, if a free choice of procedures were allowed, the PUM criterion would favour using only the at-site record. On the other hand, use of the PUM measure will allow a comparison between pooled analysis at a gauged and an ungauged site: the results provide a direct measure of the changes in the estimates due to the gauged-case weighting scheme introduced in this study. Furthermore, if the T-year estimates obtained through pooled analysis can be considered to have a lower variance than the corresponding at-site estimates, as shown by (for example) Kjeldsen and Jones (2006), then the PUM measure will reflect a practical consideration that the pooled estimates should not diverge too much from the at-site estimates in order to remain believable. The PUM values for the gauged case (weights calculated using equation (6.15)) are included as the bottom row of Table 6.3; the PUM values here are lower than the corresponding values at the ungauged site, indicating a closer correspondence to the at-site estimates.

6.7 Example: a pooling-group

The application of the new pooling procedure for both a gauged and an ungauged subject is illustrated using catchment 37017 (Blackwater at Stisted) as an example. The gauging station (37017) is located at the grid reference (5678, 2324) where the FEH CD-ROM version 2.0 gives the following relevant catchment descriptors:

AREA = 140.38 km^2 SAAR = 579 mm FARL = 0.994 FPEXT = 0.0688

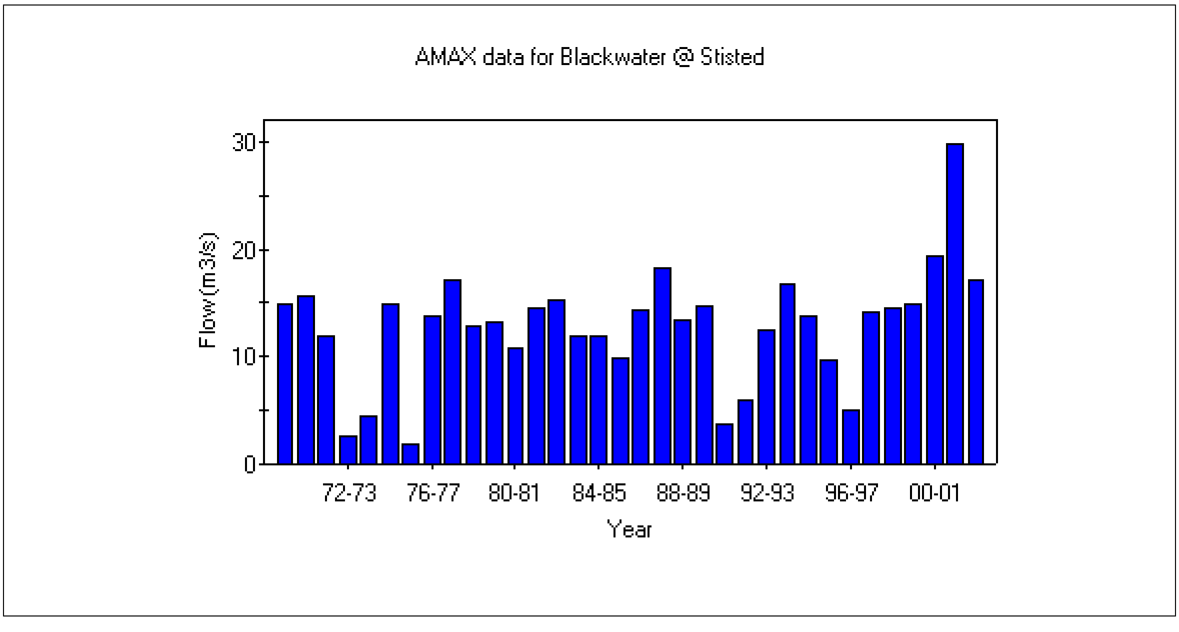


Figure 6.4 AMAX events for gauging station 37017 (from HiFlows-UK).

The AMAX record consists of 34 observations classified as ‘suitable for pooling’ by HiFlows-UK, and the time series is shown in Figure 6.4.

This example will consider the two cases where a pooling-group is created for a gauged catchment and for an ungauged catchment.

6.7.1 Selection of the pooling-group

As the pooling-group for a gauged catchment will include the gauged record itself, and the total number of AMAX events in a pooling-group must exceed 500, the pooling-groups created for the two cases (gauged and ungauged) are slightly different and shown in Tables 6.4 and 6.5, respectively.

Both pooling-groups are created by searching through the database of 602 gauged catchments, identifying the catchments most hydrologically similar as defined by the standard distance measure (*SDM*) presented in equation (6.9).

6.7.2 Review of the pooling-group

The FEH suggests that an initial pooling-group should be reviewed and, possibly, adapted. In particular, the review should consider the following factors.

- Catchment location and period of AMAX record.
- Similarity in terms of flood seasonality.
- Similarity in terms of further catchment descriptors.
- Standard comments, and other information, about catchments and their AMAX records.
- Known special features of the subject catchment.

Because the FEH derives the weights of the L-moment ratios within a pooling-group based on both ranking and record length, it is recommended that, following a review, a pooling-group can be adapted by changing the relative ranking of the catchments, or by removing or adding catchments to the initial pooling-group (or possibly both).

In the new method the weights within a pooling-group are based on record length and distance from subject site in catchment descriptor space. Therefore, the relative ranking of the catchments within a pooling-group has no influence on the weights, and the only method for adapting a pooling-group is to remove or to add individual catchments.

The FEH recommends that only catchments that can be considered ‘rural’ should be included in the pooling-group, and that for an urban subject site, any adjustment should be made after the derivation of the ‘as-rural’ growth curve. Bayliss *et al.* (2006) updated the FEH urban-adjustment procedure to use the $URBEXT_{2000}$ rather than $URBEXT_{1990}$.

Table 6.4 Pooling-group for catchment 37017 (gauged)

j	Site	No. obs.	AREA [km^2]	SAAR [mm]	FARL [-]	1-FPEXT [-]	SDM
1	37017	34	140.38	579	0.994	0.9312	0.0000
2	37020	33	132.96	588	0.982	0.9341	0.1159
3	36005	39	155.85	580	0.994	0.9236	0.1690
4	33051	34	140.09	599	0.993	0.9482	0.2010
5	38004	44	136.69	625	0.999	0.9462	0.2277
6	33018	39	132.65	661	0.986	0.9373	0.2785
7	35008	37	126.98	577	0.996	0.9012	0.3638
8	34003	44	161.41	669	0.974	0.9149	0.4044
9	30005	35	123.50	646	0.973	0.9075	0.4046
10	33055	27	101.80	579	0.999	0.9386	0.4577
11	20003	41	162.76	724	0.987	0.9548	0.5447
12	39037	31	136.48	772	1.000	0.9237	0.5588
13	21027	29	155.39	774	0.997	0.9300	0.5731
14	54106	17	185.16	677	0.993	0.9583	0.5752
15	33012	43	137.99	585	0.992	0.8793	0.5812
Total		527					

Table 6.5 Pooling-group for catchment 37017 (ungauged)

j	Site	No. obs.	AREA [km^2]	SAAR [mm]	FARL [-]	1-FPEXT [-]	SDM
1	37020	33	132.96	588	0.982	0.9341	0.1159
2	36005	39	155.85	580	0.994	0.9236	0.1690
3	33051	34	140.09	599	0.993	0.9482	0.2010
4	38004	44	136.69	625	0.999	0.9462	0.2277
5	33018	39	132.65	661	0.986	0.9373	0.2785
6	35008	37	126.98	577	0.996	0.9012	0.3638
7	34003	44	161.41	669	0.974	0.9149	0.4044
8	30005	35	123.50	646	0.973	0.9075	0.4046
9	33055	27	101.80	579	0.999	0.9386	0.4577
10	20003	41	162.76	724	0.987	0.9548	0.5447
11	39037	31	136.48	772	1.000	0.9237	0.5588
12	21027	29	155.39	774	0.997	0.9300	0.5731
13	54106	17	185.16	677	0.993	0.9583	0.5752
14	33012	43	137.99	585	0.992	0.8793	0.5812
15	54018	41	173.10	757	0.991	0.9244	0.5952
Total		534					

The improved method for pooled frequency analysis derived in this study has retained the recommendation to use only rural catchments in the pooling-group, though the threshold for definition of ‘rural’ has changed following the adoption of $URBEXT_{2000}$ rather than $URBEXT_{1990}$. Where the FEH defined rural as catchments with $URBEXT_{1990}$ values less than 0.025, this study defines rural as catchments with $URBEXT_{2000}$ values less than 0.030 (Bayliss *et al*. ,2006) See also Section 2.1.1.

Table 6.6 Calculation of pooled L-moment ratios for 37017 (gauged)

				L-CV						L-SKEW				
j	**Site**	**No. obs.**	**SDM**	b_j	c_j	$(b_j + c_j)^{-1}$	w_j	**L-CV**		b_j	c_j	$(b_j + c_j)^{-1}$	w_j	**L-SKEW**
1	37017	34	0.0000	0.00115	0.00079	515.30	0.6526	0.2232		0.00000	0.00857	116.66	0.1690	-0.0910
2	37020	33	0.1159	0.00275	0.00082	280.46	0.0327	0.2062		0.00850	0.00885	57.64	0.0835	-0.2121
3	36005	39	0.1690	0.00308	0.00069	265.32	0.0309	0.3074		0.01120	0.00741	53.72	0.0778	0.1389
4	33051	34	0.2010	0.00326	0.00079	247.06	0.0288	0.2403		0.01255	0.00857	47.34	0.0686	-0.1358
5	38004	44	0.2277	0.00339	0.00061	250.03	0.0291	0.3050		0.01356	0.00653	49.78	0.0721	0.1621
6	33018	39	0.2785	0.00363	0.00069	231.65	0.0270	0.2633		0.01517	0.00741	44.28	0.0642	0.2481
7	35008	37	0.3638	0.00398	0.00072	212.33	0.0247	0.3174		0.01721	0.00784	39.92	0.0578	0.0979
8	34003	44	0.4044	0.00414	0.00061	210.73	0.0246	0.2953		0.01795	0.00653	40.84	0.0592	0.2420
9	30005	35	0.4046	0.00414	0.00077	203.79	0.0237	0.2881		0.01796	0.00831	38.07	0.0552	0.0937
10	33055	27	0.4577	0.00433	0.00100	187.50	0.0218	0.3455		0.01875	0.01097	33.64	0.0487	0.3105
11	20003	41	0.5447	0.00462	0.00065	189.71	0.0221	0.4042		0.01972	0.00703	37.38	0.0542	0.2200
12	39037	31	0.5588	0.00466	0.00087	180.73	0.0211	0.4243		0.01985	0.00946	34.12	0.0494	0.3945
13	21027	29	0.5731	0.00471	0.00093	177.31	0.0207	0.3271		0.01997	0.01016	33.19	0.0481	0.2429
14	54106	17	0.5752	0.00471	0.00163	157.60	0.0184	0.3482		0.01999	0.01829	26.13	0.0379	0.3741
15	33012	43	0.5812	0.00473	0.00062	186.76	0.0218	0.2799		0.02003	0.00669	37.42	0.0542	0.0729
	Total =	527						**0.2514**						**0.0976**

Table 6.7 Calculation of pooled L-moment ratios for 37017 (ungauged)

				L-CV						L-SKEW				
j	**Site**	**No. obs.**	**SDM**	b_j	c_j	$(b_j + c_j)^{-1}$	w_j	**L-CV**		b_j	c_j	$(b_j + c_j)^{-1}$	w_j	**L-SKEW**
1	37020	33	0.1159	0.00275	0.00082	280.47	0.0886	0.2062		0.00850	0.00885	57.65	0.0945	-0.2121
2	36005	39	0.1690	0.00308	0.00069	265.34	0.0838	0.3074		0.01120	0.00741	53.73	0.0880	0.1389
3	33051	34	0.2010	0.00326	0.00079	247.05	0.0781	0.2403		0.01256	0.00857	47.33	0.0776	-0.1358
4	38004	44	0.2277	0.00339	0.00061	250.03	0.0790	0.3050		0.01356	0.00653	49.79	0.0816	0.1621
5	33018	39	0.2785	0.00363	0.00069	231.65	0.0732	0.2633		0.01517	0.00741	44.28	0.0726	0.2481
6	35008	37	0.3638	0.00398	0.00072	212.33	0.0671	0.3174		0.01721	0.00784	39.92	0.0654	0.0979
7	34003	44	0.4044	0.00414	0.00061	210.72	0.0666	0.2953		0.01795	0.00653	40.84	0.0669	0.2420
8	30005	35	0.4046	0.00414	0.00077	203.79	0.0644	0.2881		0.01796	0.00831	38.07	0.0624	0.0937
9	33055	27	0.4577	0.00433	0.00100	187.51	0.0592	0.3455		0.01875	0.01097	33.64	0.0551	0.3105
10	20003	41	0.5447	0.00462	0.00065	189.72	0.0599	0.4042		0.01972	0.00703	37.38	0.0612	0.2200
11	39037	31	0.5588	0.00466	0.00087	180.73	0.0571	0.4243		0.01985	0.00946	34.12	0.0559	0.3945
12	21027	29	0.5731	0.00471	0.00093	177.31	0.0560	0.3271		0.01997	0.01016	33.19	0.0544	0.2429
13	54106	17	0.5752	0.00471	0.00163	157.60	0.0498	0.3482		0.01999	0.01829	26.13	0.0428	0.3741
14	33012	43	0.5812	0.00473	0.00062	186.77	0.0590	0.2799		0.02003	0.00669	37.42	0.0613	0.0729
15	54018	41	0.5952	0.00478	0.00065	184.22	0.0582	0.1546		0.02014	0.00703	36.80	0.0603	0.1323
	Total =	534						**0.2958**						**0.1357**

6.7.3 Deriving the pooling-group estimates

For the new pooling procedure developed in this study, the weights assigned to the individual values of L-CV and L-SKEW within a particular pooling-group are conditional on whether the pooling-group is formed for a gauged or an ungauged catchment. For a gauged catchment (the example in Table 6.4), the weights are calculated using equations (6.14) and (6.15), and for an ungauged catchment (the example in Table 6.5) using equation (6.13). In both cases, the parameters b_i and c_j are estimated using equations (6.18), (6.19) and (6.22). The resulting weights and pooled L-moment ratios for catchment 37017 for both the gauged and the ungauged pooling-groups are shown in Table 6.6 and Table 6.7 respectively. The pooled L-moment ratios are estimated as the weighted average of the individual L-moment ratios. Note that the values of the pooled L-moment ratios are highlighted in bold on the last line in each table.

6.7.4 Discussion of the pooling-group

Tables 6.6 and 6.7 contain details of some of the intermediate steps in the construction of the pooling-group estimates of L-CV and L-SKEW. Although these tables relate to only the single example, and are derived using the rules previously described, the following general points may be made.

- The coefficients b_j increase with the similarity distance measure (*SDM*), which is the main reason why the weights for each catchment tend to decrease with distance. The increase of the coefficients b_j relates to the increase of the variogram functions shown in Figure 6.2. For this example, the range of values of *SDM* is not large enough to show that for L-SKEW, the values of b_j approach a constant value as the distance increases: this means that once the distance is large enough, each catchment of equal record length is of equal worth. In contrast, for L-CV, the values of b_j would continue to increase with *SDM*.
- The coefficients c_j are smaller for those catchments with a long record length, which means that these catchments are given a slightly greater weight w_j than those at with shorter records having about the same *SDM* value.
- The relative numerical sizes of the coefficients are such that, except for those catchments which are very close to the subject catchment according to the SDM criterion, the values of b_j dominate those of c_j. This means that, apart from the four or five nearest catchments, the record length available at a particular catchment has only a modest effect on the weights w_j, unless the record length is very short. However, the effect of record length will be relatively greater for L-SKEW than for L-CV. For example, one might consider what would result if, in Tables 6.4 and 6.5, catchment 54106 (position 14 or 13 in the list), which has a record length of 17, had instead had a record length of either 4 or 72. For simplicity it is easiest to consider the comparison assuming that members of the pooling-group are not re-selected because of the change in record length.
    - For a record length of 4, the values of c_j would have been changed to 0.00870 and 0.13715 for L-CV and L-SKEW respectively. This would lead to the raw weights $(b_j + c_j)^{-1}$ being changed to 74.6 and 6.36. Thus the effect of the change in record length on the final weights w_j would be to multiply the raw weights by factors of 0.47 and 0.24.
    - For a record length of 72 instead of 17, the values of c_j would have been 0.00041 and 0.00392, and the raw weights would have been 195.3

and 41.8: thus the effect would have been to multiply the raw weights by factors of 1.23 and 1.60.

- There is a limit to how large the raw weights $\left(b_j + c_j\right)^{-1}$ can be. These weights increase as the record length for the contributing catchment increases, but can never be larger than b_j^{-1}. This can be used to show that, in the case of L-CV, if a very large number of catchments are included in a pooling-group, the weights w_j would tend to continue to decrease towards zero for increasing values of *SDM*. In contrast, in the case of L-SKEW, the weights w_j would tend to fluctuate about a constant level for those catchments with high SDM values.

The sensitivity of the new weighting scheme to the record-length at the gauged catchment is further illustrated. Starting with the pooling-group for the gauged catchment (37017) in Table 6.6, the weights have been re-evaluated assuming that the gauged catchment had records of different lengths. The results in Table 6.8 show how the weight assigned to the gauged catchment for L-CV and for L-SKEW change as the record-length changes. Note that when the weight of the gauged catchment changes, the weighting assigned to all other catchments is rescaled to ensure that all weights sum up to one. This is illustrated in Table 6.8 by showing the effect of the changed record length for the gauged catchment on the weight given to the next nearest catchment (catchment 37020).

Table 6.8 Weighting of L-CV and L-SKEW for a gauged catchment as a function of the record-length at that catchment.

Record length	**Weight assigned to gauged catchment 37017**		**Weight assigned to ungauged catchment 37020**	
	L-CV	L-SKEW	L-CV	L-SKEW
4 years	0.1459	0.0126	0.0840	0.0993
34 years	0.6526	0.1690	0.0327	0.0835
72 years	0.8017	0.3080	0.0187	0.0696
120 years	0.8714	0.4286	0.0121	0.0574

In this example, the gauged catchment (37017) is given much greater weight in the average for L-CV than the next most similar catchment and this is true even if the record length is quite short. In the case of L-SKEW, the special weight given to the gauged catchment is much smaller than the weight used for L-CV and, for very short records, the weight is less than that given to the next nearest catchment (which has a longer record length). This contrast in the special weights used for L-CV and L_SKEW reflects the much larger contribution of sampling error in the case of L-SKEW compared to that of L-CV. Relative to the differences between catchments, the sample estimate of L-CV for a catchment is likely to be closer to its true value than is the sample estimate of L-SKEW. It can be seen in Table 6.8 that, even if the subject catchment has a record length of 120 years, a modest total weight of 0.1286 is still being given to the other catchments in the pooling-group for L-CV, while for L-SKEW the other catchments receive a substantial total weight of 0.5714. These calculations have been done on the basis that the catchments selected for the pooling group are not changed as the record length for the subject catchment changes, whereas additional or fewer catchments should be used according to the rule on total record length. However, the effect should be small in this context.

6.7.5 Results from the pooling-group

By adopting a GLO distribution, the growth curve is given as

$$z_T = 1 + \frac{\beta}{\kappa}\left(1 - (T-1)^{-\kappa}\right). \qquad (6.23)$$

Where T is the return period and κ and β are GLO model parameters estimated from the higher order L-moments L-CV (t_2) and L-SKEW (t_3) as

$$\hat{\kappa} = -t_3,$$
$$\hat{\beta} = \frac{t_2 \hat{\kappa} \sin(\pi\hat{\kappa})}{\hat{\kappa}\pi(\hat{\kappa} + t_2) - t_2 \sin(\pi\hat{\kappa})}. \qquad (6.24)$$

The GLO parameters for the single site, gauged and ungauged pooling-groups are shown in Table 6.9. The L-moment ratios for the three cases can be found in Tables 6.6 and 6.7 above.

Table 6.9 GLO model parameters for catchment 37017 for single site, gauged and ungauged pooling-groups.

Method	**L-CV**	**L-SKEW**	κ	β
Single site	0.2232	-0.0908	0.0908	0.2131
Pooled (gauged)	0.2514	0.0976	-0.0976	0.2579
Pooled (ungauged)	0.2958	0.1357	-0.1357	0.3070

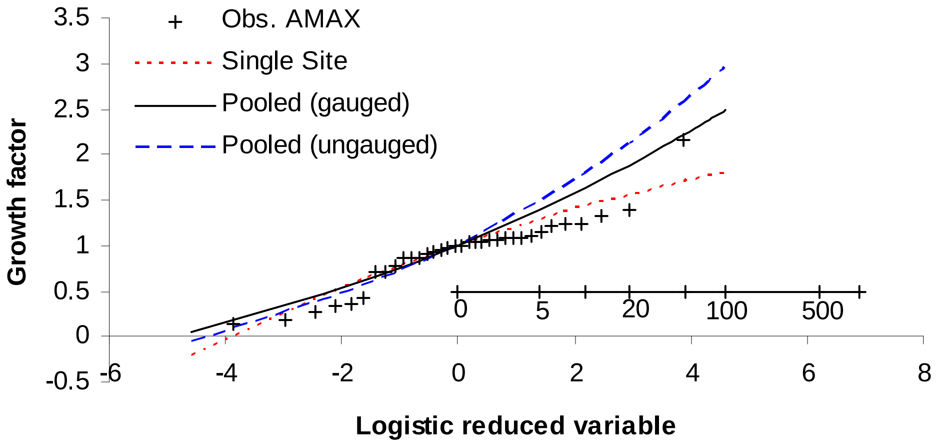


Figure 6.5 Comparison of growth curves for catchment 37017 for: single site, gauged and ungauged pooled analysis. Also shown are the observed AMAX data from HiFlows-UK.

Figure 6.5 shows the three growth curves plotted against return period together with the AMAX series for catchment 37017, available from HiFlows-UK. The plotting positions for the observed AMAX events are calculated using a Gringorten plotting position. In Figure 6.5 it can be observed that both of the pooled growth curves are steeper than the single site growth curve. The growth curve derived from the pooling-group created for the gauged site is closer to the single site curve than the corresponding curve derived from the ungauged growth curve, which is to be expected when using the new weighting scheme introduced in this study.

6.8 Comparison of results for 100-year return period

When using the index-flood method the T-year event, x_T or Q_T here, is calculated as the product of the index flood, QMED, and the T-year growth factor, z_T, as described in Section 6.1. In Section 4.6, a comparison was presented between estimates of QMED (the index flood) based on catchment descriptors from the QMED equation developed in this study, equation (4.13), and from the FEH equation, respectively. This section presents a comparison of the differences between both the 100-year growth factors and the 100-year floods (i.e. z_T and Q_T for T=100) as estimated for an ungauged site using the pooling procedure developed in this study and the FEH methodology. Both sets of estimates are based on the HiFlows-UK data-set used in this study.

The comparison assumes the subject site to be ungauged, which means that the AMAX record for each subject site is not included in its own pooling-group. For both the new method and the FEH method, the 100-year events were estimated based on the 602 AMAX series from the HiFlows-UK dataset used in this study. As in section 6.6.1, the FEH methodology forms pooling-groups based on hydrological similarity as defined in the FEH (i.e. using ln[AREA], ln[SAAR] and BFIHOST) and each pooling-group has a target size of 500 AMAX events.

The ratio between the 100-year growth factors (z_{100}) estimated at each of the 602 catchments is shown in Figure 6.6. It can be seen that the growth factors obtained from the two methods are generally within ±25 per cent of each other. Also, no geographical pattern in the direction of change can readily be observed in Figure 6.6. However, it is worth noticing that the results in Table 6.3 indicated that the new pooling procedure performs better than the FEH procedure, i.e. gives estimates of the growth factor at the ungauged site closer to the estimates that would have been obtained if at-site data had been available. This type of comparison cannot be made using Figure 6.6.

The changes in the growth factors can be summarised as follows. Changes in the estimated 100-year growth factors range from ratios of 0.66 to 1.65, with half being greater than 1.00 (25 per cent of the ratios are less than 0.93, and 25 per cent are greater than 1.09). Here a ratio greater than one indicates that the new procedure produces estimates larger than the FEH procedure. These quantitative results indicate that the estimated growth curve shows little change for around half of the catchments.

The estimates of the 100-year flood quantiles obtained using the procedure developed in this study and the FEH procedure are compared in Figure 6.7. The new procedure (consisting of the revised regression equation for QMED and the revised pooling-group procedure) gives estimates of the 100-year flood that are lower than the FEH method in the east of England, but higher estimates in West England, Wales, Scotland and Northern Ireland. More quantitatively, changes in the estimated 100-year floods range from ratios of 0.48 to 2.24, with half being greater than 1.14 (25 per cent of the ratios are less than 0.97 and 25 per cent are greater than 1.32). Here a ratio greater than one indicates that the new procedure produces estimates larger than the FEH procedure.

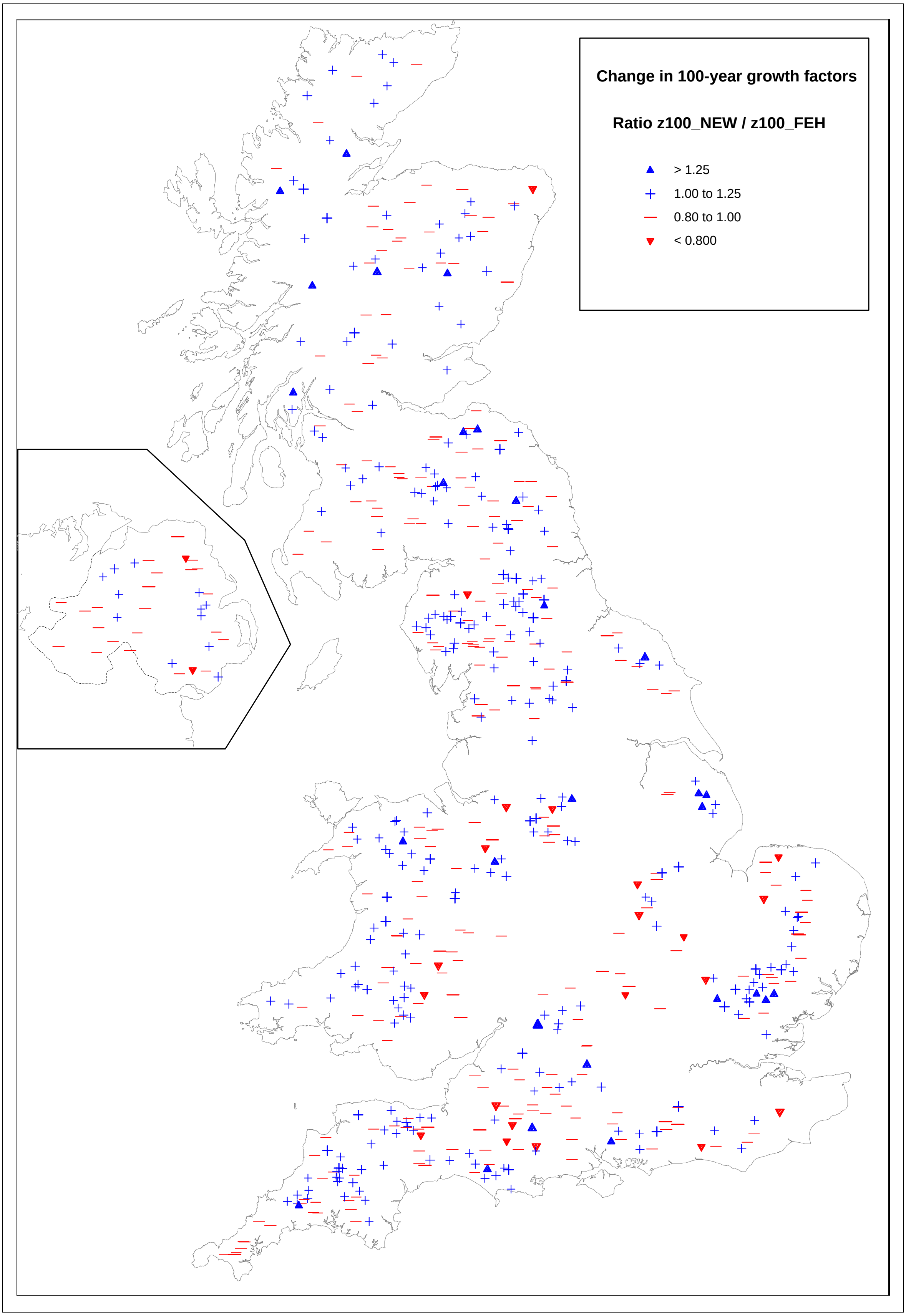


Figure 6.6 Comparison of growth curve estimates, z_{100}, for ungauged catchments using i) the new pooling method and ii) the FEH pooling method.

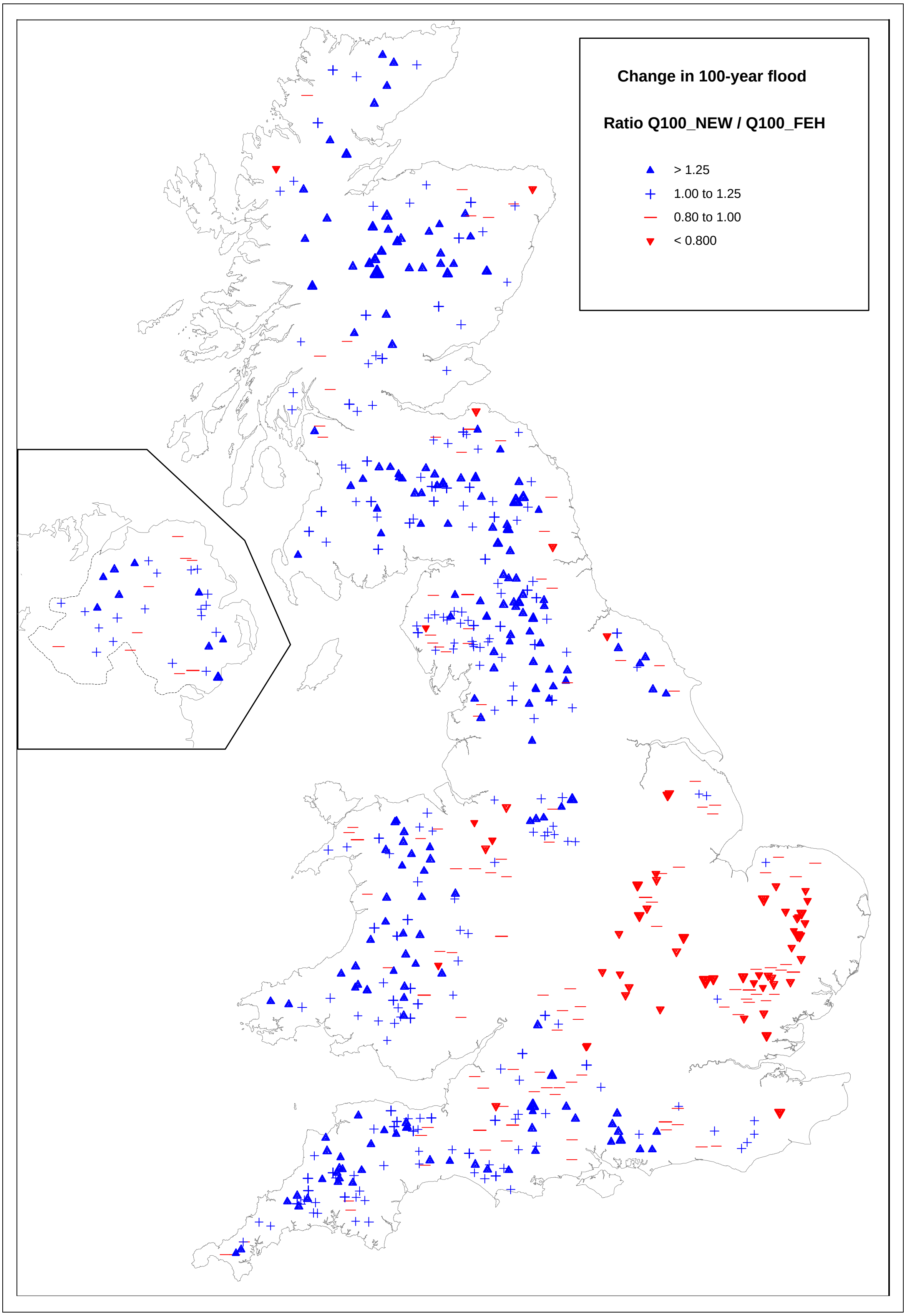


Figure 6.7 Comparison of Q_{100} estimated for ungauged catchments as the final estimates from i) the new recommendations and ii) the FEH procedure.

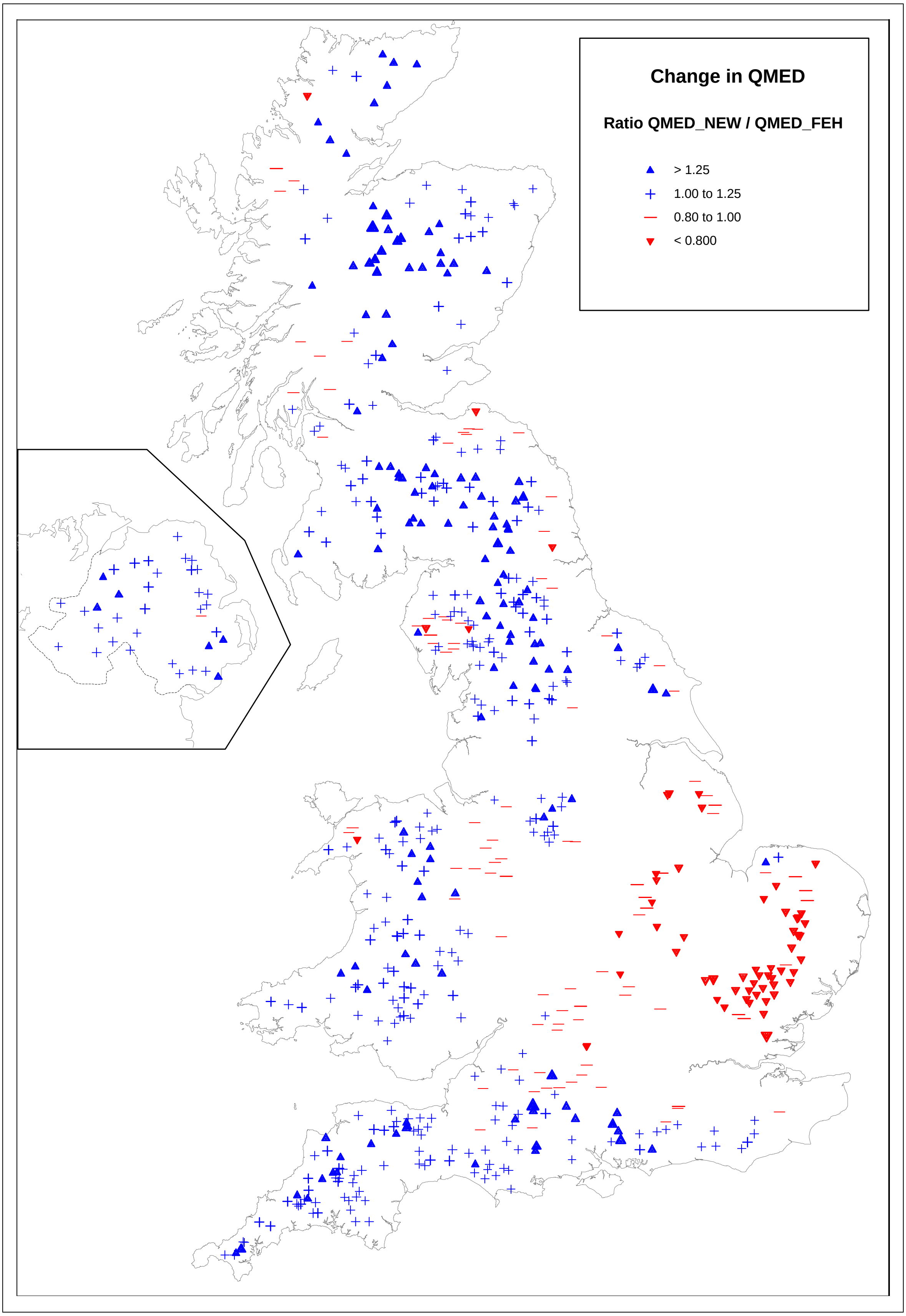


Figure 6.8 Comparison of Q_2 (QMED) estimated for ungauged catchments from i) the new recommendations and ii) the FEH procedure.

For comparison, Figure 6.8 is a copy of Figure 4.6, showing the changes in QMED (Q_2) between the new recommendation and the FEH procedure. On comparing this map to Figure 6.7, which shows the ratios between the 100-year events, Q_{100}, it is clear that it is the differences in the estimates of QMED that have the largest influence on the spatial pattern of the changes in Q_{100}. This was to be expected, given the relative sizes of the changes in QMED and z_{100} that have been found. Table 6.10 summarises the results already quoted for the changes in QMED, the 100-year growth factor z_{100} and the 100-year flood, Q_{100}.

Table 6.10 Summary of the effects of moving from the FEH procedures to the new recommendations

	Percentage points of ratio (new / FEH) across 602 catchments				
Quantity	**minimum**	**25%**	**50%**	**75%**	**maximum**
QMED	0.55	1.00	1.15	1.24	2.01
z_{100}	0.66	0.93	1.00	1.09	1.65
Q_{100}	0.48	0.97	1.14	1.32	2.24

7 Default distribution

The FEH (Vol. 3, Section 17.3.2) tested the goodness of fit of various candidate families of distributions, which suggested that the GLO distribution would be a generally applicable distribution for flood estimation in the UK. This test of fit was based on the work by Hosking and Wallis (1997: Section 5.2). A later report (Morris, 2003) raised the concern that the test of fit, as used in the FEH, was structured in such a way that the estimates of L-moment ratios used as the "pooling-group estimates" were calculated using a simple weighting scheme that was not the same as that put forward as the weighting scheme suggested to users of the FEH methodology, and concerns were raised that the results might be somewhat affected, or that at least there was some inconsistency.

7.1 The Hosking and Wallis test

It should first be noted that, while Hosking and Wallis (1997) proposed their suggested test in a pooling-group context ("regionalisation" in their terminology), the test is applicable even to records for individual catchments. It is therefore of interest to consider in general terms the effect of the number of catchments in the pooling-group on this test, as this gives some guidance regarding the importance of the weighting scheme used within the test. The test is a comparison of the raw sample-based estimate of the L-Kurtosis with the value of the L-Kurtosis predicted by a fitted model. This difference is scaled by a value for the standard deviation which essentially measures how well the difference is estimated from the data contributing to the estimate of the difference. In the present circumstances, one may think of the difference in the L-Kurtosis values as being relatively fixed (if there really is a lack of fit) as more catchments are added to the pooling-group, while the variability of the difference decreases (because a better estimate of the difference is obtained by using data from extra catchments). Thus the standard deviation used for the devisor would go down and larger values of the test statistic would result, leading to more rejections of the hypothesis of an adequate fit, since the test-statistic is judged against a fixed critical value. The use of a larger pooling-group effectively increases the power of the test. However, the size of the pooling-group needs to be restricted to a size such that the assumption used within the test remains appropriate. Specifically, that it is reasonable to use a single common distribution to represent the standardised flood distribution for all catchments in the pooling-group.

The above considerations can be extended to consider the effects of spatial dependence on the test results. The values of the standard deviation used in the test are obtained by simulation of independently distributed flood-values for the catchments before these are combined, via weighted averages, into estimates of the 3rd and 4th L-moment ratios for the pooling-group. However, the presence of spatial dependence in the real data, and its absence in the simulated data, means that the simulations will under-estimate the variability of these pooled L-moment ratios. The standard deviation used as the divisor in the test will therefore be too small compared to the quantity that should ideally be used in the test. Thus (positive) spatial dependence will tend to lead to higher (more extreme) values of the test statistic, and this will lead to the null hypothesis that a given family of distribution fits being rejected too often compared to the target frequency for false rejections.

The role of the specific weighting scheme used to estimate the pooled L-moment ratios can also be considered. Firstly, it is important that exactly the same weighting scheme is used in calculating both the L-moment ratios used to calculate the difference of the L-Kurtosis values for the actual data, and for the equivalent steps when applied to the simulated data. This has always been the case. Secondly, given this assumption, the effect of changing the weighting scheme for a given number of catchments will be similar to changing the number of catchments used in a fixed weighting scheme. Thus some weighting schemes may give more precise estimates of the difference of the two L-Kurtoses and lead to more power for the test. Using a weighting scheme within the test that is not “optimal” does not invalidate the test.

It should also be recalled that the test statistic suggested by Hosking and Wallis (1997) has been used not only for formal tests for whether there is enough evidence to reject the choice of a given 3-parameter family of distributions, but also as a way of indicating which of a number of families is “best”. In this instance, for a given pooling-group, equivalent test-statistics are calculated for a number of candidate families and the family for which the test-statistic is smallest (or indicates least lack-of-fit). This usage should not be badly affected by the problem relating to the inadequate representation of spatial dependence of the annual maximum values, since the statistics for each of the families should be affected roughly equally.

7.2 Revision of the Hosking and Wallis test

On examining the principles behind the test of lack-of-fit as set-out by Hosking & Wallis (1997), a number of points arise. Some of these points are treated in more detail here. These considerations have led to the formulation of an alternative test-statistic which looks superficially similar to that of Hosking and Wallis, but the details of the calculations are rather different. A simulation-based study similar to that reported by Hosking and Wallis (1997; Table 5.2) has shown that the version of the statistic adopted here has properties which are superior to those of the original, in terms of having a much better match to the target acceptance rate of 90 per cent when the test is applied to cases where the distribution being tested is the same as the distribution from which the simulated data were generated

As discussed above, it seems likely that the effect of spatial dependence would mean that the variance estimated from independent samples would be too small and thus that more “rejections” of the individual tests would occur than the notional frequencies of 90 per cent acceptances and 10 per cent rejections for a critical value of $|Z|$ of 1.64. The relative acceptability of the candidate distributions should be unaffected. In contrast, the effect of heterogeneity should be broadly neutral, provided that the distributions associated with each site are treated as fixed in the simulations.

Hosking and Wallis (1997) define the basis of their test-statistic in their Equation (5.3) in the following way, although a modified notation is used here. Firstly, the test is based on the idea that, for the 3-parameter distributions being treated, the theoretical value (according to the fitted distribution) of the L-Kurtosis can be evaluated and compared with the sample estimate of the L-Kurtosis obtained directly from the data. The existing methods of fitting the 3-parameter distributions that are being considered do not make any use of the sample L-Kurtosis and the basis of the test is to compare the sample L-Kurtosis with the model-derived L-Kurtosis for the fitted model. In practice, these model-derived values for the 4th L-moment ratio, t_4^{DIST} , are obtained as a fixed (distribution-dependent) function of the L-Skewness (3rd L-moment ratio):

$$t_4^{DIST} = h_{DIST}(t_3)$$

where h_{DIST} is the function that gives the theoretical L-Kurtosis in terms of the theoretical L-Skewness

$$\tau_4^{DIST} = h_{DIST}(\tau_3) \ ,$$

and where t_3 is the sample L-Skewness. The basic form of the test statistic is defined as

$$Z^{DIST} = \frac{t_4 - t_4^{DIST}}{\sigma_4}$$

where σ_4 represents a standard deviation to be discussed later. The sample L-Kurtosis, t_4, and the sample L-Skewness, t_3 (from which t_4^{DIST} is derived) are both derived by a pooling-group scheme if more than one catchment is being considered, otherwise the usual single-catchment estimates would be used.

Note that Hosking and Wallis present a revised formulation (their equation (5.6)) which, with a reversal of sign to accord with the above, gives the final version of the test statistics as

$$Z^{DIST} = \frac{t_4 - t_4^{DIST} - B_4}{\sigma_4}$$

where B_4 is a bias correction term. In the revised version used here, the bias correction term is much smaller than in the original and can be omitted without much effect. Hosking and Wallis (1997) gave a complicated expression for σ_4, involving B_4, but this can be simplified to being identical to the sample variance of certain simulated quantities. In addition, Hosking and Wallis's equation (5.6) is given with τ_4^{DIST} instead of t_4^{DIST}, presumably to indicate that the value is treated as fixed (see below).

According to the approach of Hosking and Wallis, σ_4 should be the standard deviation of t_4. However, it is arguable that σ_4^{DIST} should be the standard deviation of $t_4 - t_4^{DIST}$, which might well be a rather smaller quantity. An alternative is that σ_4^{DIST} should be the conditional variance of t_4 given t_4^{DIST}, but this would be rather more complicated to turn into a practical procedure. The question here is what should be treated as being the test statistic. The choices are t_4, $\left(t_4 - t_4^{DIST}\right)$ or $\left(t_4 \middle| t_4^{DIST}\right)$. One of the revisions to the procedure that has been adopted here is to treat $\left(t_4 - t_4^{DIST}\right)$ as the test statistic.

The Hosking and Wallis procedure is to test several families of distributions simultaneously for their lack of fit and to do so using a single base set of simulations from a Kappa distribution (which is a 4-parameter family of distributions). Thus the simulations are for a distribution which does not have theoretical L-moment ratios that correspond to $\left(t, t_3, t_4^{DIST}\right)$, but rather has L-moment ratios $\left(t, t_3, t_4\right)$. While some arguments can be made that support this, it seems better to perform separate sets of simulations using whichever distribution is being tested to generate the simulated data. This eliminates several approximations and correction-terms that are required in the argument needed to support the use of a single common set of simulations.

7.3 The test procedure

The procedure for testing the goodness of fit of a given family of distributions is as follows.

- Calculate the observed test statistic $T_{obs} = \left(t_4 - t_4^{DIST}\right)$.
- Calculate a number, N, of simulated versions of the test statistic $\left\{T_{sim}^{(i)}; i = 1, \ldots, N\right\}$ using Monte Carlo simulations. Each of these simulated test statistics is calculated by constructing a set of data of the same size as the observed data (in terms of the number of sites in the pooling-group and the record lengths) independently between years and sites, from the distribution in the given family

which has the observed L-moment ratios (t_3, t_4) and a unit mean. In particular, this means calculating simulated versions of t_3 and t_4 and then using the former to calculate $t_4^{DIST} = h_{DIST}(t_3)$ from the simulated value of t_3. Finally, the simulated values of the test statistic is calculated as $T_{sim}^{(i)} = (t_4 - t_4^{DIST})$.

- Calculate the sample mean B_4, and the sample variance, σ_4^2, from the set of simulated test statistics $\{T_{sim}^{(i)}; i = 1, \dots, N\}$.
- Calculate the test statistic $Z^{DIST} = \dfrac{t_4 - t_4^{DIST} - B_4}{\sigma_4}$.
- Compare the absolute value $|Z^{DIST}|$ with 1.64, and count the fit as acceptable if $|Z^{DIST}| \le 1.64$. Otherwise reject the particular family of distributions for the particular pooling-group.

As noted earlier, the bias correction B_4 is small and can be omitted. It is important that the test statistics carried over from the individual simulated data sets are the differences $T_{sim}^{(i)} = (t_4 - t_4^{DIST})$ and not just the L-kurtosis t_4 as used by Hosking & Wallis (1997).

7.4 Results

This section summarises the results obtained by applying the test procedure outlined above in Section 7.2 to pooling-groups formed as outlined in Chapter 6 (considering the catchment to be ungauged) for each of the 602 catchments used in this study. The following five 3-parameter distributions were considered as possible candidate distributions:

- Generalised Logistic (GLO).
- Generalised Extreme Value (GEV).
- Generalised Normal (GNO), also known as the 3-parameter Log-Normal.
- Person type 3 (PE3).
- Generalised Pareto (GPA).

For a further description of each of these distributions, please refer to the FEH (Vol. 3, Chapter 15) or Hosking and Wallis (1997).

The results of the analysis are summarised in Table 7.1, where the first row (labelled "Chosen") contains the number of times (out of 602) that a particular distribution was chosen as the preferred option (smallest value of $|Z^{DIST}|$). The second row (labelled "Accepted") contains the number of times a particular distribution gave a value of the test statistic satisfying $|Z^{DIST}| \le 1.64$. Finally, the last row (labelled "Rejected") counts the number of times a particular distribution was rejected.

Table 7.1 Results of the goodness of fit test applied to pooling-groups formed for each of the 602 catchments.

Test	GLO	GEV	GNO	PE3	GPA
Chosen	283	167	106	46	0
Accepted	364	358	339	209	0
Rejected	238	244	263	393	602

From the results in Table 7.1, it is clear that the GLO distribution remains the best choice for a default UK distribution as it is both chosen and accepted more often than any of the other candidate distributions. However, the results for the two distributions are somewhat closer than reported for the FEH study. The numbers of catchments for which the GLO and GEV distributions are “accepted” are almost equal, but the comparison favours the GLO marginally. While it appears that the main distinction in the results between the GLO and GEV distributions lies in the number of times that the distribution is chosen as having the “best” fit, it should be recalled that this comparison is affected by which other distributions have been included in the competing set. It is not clear how many of the catchments which have the GNO, PE3 and GPA distributions as their “chosen” distributions would select the GLO if the only options were GLO and GEV.

8 Summary of new flood estimation procedures

This chapter provides a short summary of the new procedures introduced in this project. While maintaining the conceptual basis of the index-flood method, as implemented in the FEH, the work undertaken in the current project has improved the estimation of QMED and the growth curve at both gauged and ungauged catchments.

8.1 Estimation of QMED

The recommended method for estimating the index flood (QMED) depends on whether the subject site is a gauged or an ungauged catchment.

8.1.1 Estimating QMED at a gauged catchment

Detailed guidelines for estimation of QMED from flood data were provided as part of the FEH (Vol.3 Ch. 2). No further investigation into this aspect of the method has been undertaken as part of this study. Note that for the development of the regression model linking QMED to catchment descriptors (the QMED model) in the current study, all sample values of QMED were estimated as the median of the AMAX series regardless of record length. Also, the QMED values were not subjected to adjustment for climatic variation as in the FEH.

8.1.2 Estimating QMED at an ungauged catchment

When no flood data are available at the site of interest, QMED has to be estimated either from catchment descriptors (possibly including data transfer from a nearby gauged donor catchment) or using some other method.

Catchment descriptors

The QMED for rural catchments can be estimated as

$$QMED = 8.3062 AREA^{0.8510}\, 0.1536^{\left(\frac{1000}{SAAR}\right)} FARL^{3.4451}\, 0.0460^{BFIHOST^2} . \qquad (8.1)$$

The catchment descriptors are available from the FEH CD-ROM Version 2 for all catchments in the UK larger than 0.5 km^2. The factorial standard error (*fse*) of the estimated QMED values is 1.431, which is a 7.5 per cent reduction compared to the *fse* value of 1.541 reported for the original FEH QMED equation.

The FEH emphasises that the uncertainty of QMED estimated using the QMED equation is generally much larger than the uncertainty of estimates obtained directly from flood data. Consequently, the FEH recommends that data transfer from nearby gauged donor or analogue catchments should be used wherever possible. However, based on research by Kjeldsen and Jones (2007) and results obtained in this study, it is found that the benefits of donor sites are generally less than previously thought. It is therefore recommended that the data transfer procedure is revised to account for the geographical distance between the centroids of the target catchment and a donor catchment as

$$QMED_{s,adj} = QMED_{s,cds}\left(\frac{QMED_{g,obs}}{QMED_{g,cds}}\right)^{a_{sg}}, \qquad (8.2)$$

where

$$a_{sg} = 0.4598\exp\left(-0.0200d_{sg}\right) + \left(1-0.4598\right)\exp\left(-0.4785d_{sg}\right),$$

and where d_{sg} is the geographical distance (km) between the subject site and the gauged donor site.

The donor adjustment in the form given in equation (8.2) will automatically reduce the influence of the donor site as the geographical distance between the two catchment centroids increases. For example, the adjustment term a_{sg} is less than 0.1 when the inter-centroid distance is greater than about 76km.

Other methods

The FEH provided tentative advice on other methods for estimating QMED when no flood data are available, including obtaining QMED from rainfall-runoff modelling and a relationship between QMED and river channel dimensions. No research has been undertaken as part of this study to further investigate and improve the usefulness of these methods.

8.2 Estimation of the growth curve

The estimation of the growth curve is based on the pooling-group method and requires i) the formation of a pooling-group followed by ii) estimation of the pooled distribution parameters through the method of L-moments using the weighted average of the L-moment ratios within the pooling-group.

8.2.1 Selecting a pooling-group

As in the FEH, a pooling-group for a particular site of interest is formed by identifying a number of gauged catchments classified as hydrologically similar. The selection of catchments is based on a distance measure, measuring the distance in a catchment descriptor space defined by ln[AREA], ln[SAAR], FARL and FPEXT and calculated as

$$SDM_{ij} = \sqrt{3.2\left(\frac{\ln AREA_i - \ln AREA_j}{1.28}\right)^2 + 0.5\left(\frac{\ln SAAR_i - \ln SAAR_j}{0.37}\right)^2 + 0.1\left(\frac{FARL_i - FARL_j}{0.05}\right)^2 + 0.2\left(\frac{FPEXT_i - FPEXT_j}{0.04}\right)^2}. \qquad (8.3)$$

The FEH recommended that the size of the pooling-group should vary according to the target return period such that the total number of AMAX events should be at least 5 times the return period (the 5T rule). However, it was found that a default pooling-group size consisting of 500 AMAX events performed well for a range of return periods.

Detailed instructions of how to review and adapt the initial pooling-group were presented in the FEH. The main differences between the FEH and the revised method presented here are due to the new weighting scheme presented in the next section, however the main points of difference are summarised below. Firstly, the new weighting scheme assigns weight to each individual catchment in the pooling-group based on the distance in catchment space from the target site rather than on rank within the pooling-group. Hence, moving catchments up or down in the ranking order within the pooling-group will not change the weights. Secondly, the weighting scheme will differentiate between a gauged and an ungauged catchment and derive weights differently for the two cases. Finally, two separate sets of weights are used for the calculation of pooled L-CV and L-SKEW values.

8.2.2 Estimating the pooled growth curve

As in the FEH, the pooled growth curve is derived using the pooled L-moment ratios derived from the *M* sites in a pooling-group. For a GLO distribution, the mathematical form of the pooled growth curve is defined as

$$z_T^P = 1 + \frac{\beta^P}{\kappa^P}\left(1 - (T-1)^{\kappa^P}\right), \tag{8.4}$$

where the superscript P indicates that a parameter is based on pooled data. The pooled GLO parameters are estimated using the pooled L-moment ratios as

$$\begin{aligned} \hat{\kappa}^P &= -t_3^P, \\ \hat{\beta}^P &= \frac{t_2^P \hat{\kappa}^P \sin\left(\pi\hat{\kappa}^P\right)}{\hat{\kappa}^P \pi\left(\hat{\kappa} + t_2^P\right) - t_2^P \sin\left(\pi\hat{\kappa}^P\right)}. \end{aligned} \tag{8.5}$$

The pooled L-moment ratios, t_2^P and t_3^P, are calculated as the weighted average of the L-moment ratios for each individual catchment in the pooling-group. For both L-CV and L-SKEW, the weighted average is defined as

$$t_r^P = \sum_{j=1}^{M} \omega_j t_{r,j} \quad (r = 2,3), \tag{8.6}$$

where the weights depends on whether or not the site of interest is gauged or ungauged, the record length and the distance in catchment descriptor space from the target site for each individual site. Whereas the FEH used the same set of weights for both L-CV and L-SKEW, this study has developed a different set of weights for each of the two L-moment ratios.

No information at target catchment (ungauged)

For a pooling-group created for an ungauged site, the weights assigned to L-CV and L-SKEW for each catchment are defined as

$$\text{L-CV} \qquad \omega_j = \frac{\left(c_j + b_j\right)^{-1}}{\sum_{k=1}^{M}\left(c_k + b_k\right)^{-1}}, \quad j = 1,\ldots,M. \tag{8.7}$$

L-SKEW $$\omega_j = \frac{\left(c_j + b_j\right)^{-1}}{\sum_{k=1}^{M}\left(c_k + b_k\right)^{-1}}, \quad j = 1, \ldots, M. \tag{8.8}$$

In the above, the quantity b_j is defined separately for L-CV and L-SKEW as

L-CV $$b_j = \left(0.0047\sqrt{SDM_j} + \frac{0.0023}{2}\right), \tag{8.9}$$

L-SKEW $$b_j = 0.0219\left(1 - \exp\left[-\frac{SDM_j}{0.2360}\right]\right), \tag{8.10}$$

and the sampling variance c_k is defined for L-CV and L-SKEW as

L-CV $$c_k = \frac{0.02609}{n_k - 1} \tag{8.11}$$

L-SKEW $$c_k = \frac{0.2743}{n_k - 2} \tag{8.12}$$

where n_k is the record-length at the k'th site. Details of the development of equations (8.9) to (8.12) are provided in Chapter 6.

Data available at the subject catchment (gauged)

When data are available at the subject catchment, a special (large) weight is assigned to the at-site data (catchment number $j = 1$) to emphasise the importance of at-site data compared to the other catchments in the pooling-group. When conducting a pooled analysis at a gauged site, different sets of weights are used for L-CV and L-SKEW.

For L-CV, the weighting scheme for a gauged catchment is defined as

$$\omega_1 = \frac{b_1}{c_1 + b_1} + c_1 \frac{\left(c_1 + b_1\right)^{-2}}{\sum_{k=1}^{M}\left(c_k + b_k\right)^{-1}}, \quad j = 1 \tag{8.13}$$

$$\omega_j = \frac{c_1\left(c_1 + b_1\right)^{-1}\left(c_j + b_j\right)^{-1}}{\sum_{k=1}^{M}\left(c_k + b_k\right)^{-1}}, \quad j = 2, \ldots, M \tag{8.14}$$

The quantity b_j is defined in equation (8.9) and the sampling variance c_j is defined in equation (8.11).

For L-SKEW, the weighting scheme used for gauged catchment is similar to the scheme used for the ungauged catchment:

$$\omega_j = \frac{\left(c_j + b_j\right)^{-1}}{\sum_{k=1}^{M}\left(c_k + b_k\right)^{-1}}, \quad j = 1, \ldots, M. \tag{8.15}$$

Again, details of b_j and c_j can be found in equations (8.10) and (8.12), respectively. Note that for the gauged case, the first catchment (*j* = 1) in the pooling-group is the actual target site and therefore SDM_{sj} is the distance from the target site to itself and therefore b_1 equals zero for L-SKEW. In the ungauged case, the distance between the (ungauged) target site and the first member of the pooling-group is larger than zero (with the exception of the very unlikely case where the two catchments have identical catchment descriptor values of ln[AREA], ln[SAAR], FARL and FPEXT).

8.3 Estimation of the flood frequency curve

The index-flood method constructs the flood frequency curve, x_T , as a product of the index flood, QMED, and the dimensionless growth curve, z_T, as

$$x_T = QMED\ z_T\ , \tag{8.16}$$

where T is the return period in years. When the growth curve is obtained using the pooling-group procedure (Section 8.2), z_T is obtained as z_T^P in equation (8.4).

9 Conclusions

The research presented in this report constitutes an improvement to the existing FEH statistical procedures for flood frequency estimation. The improvements are a result of both i) new modelling techniques and ii) an updated data set (HiFlows-UK). The statistical procedures outlined in the FEH made the region-of-influence approach operational in the UK, which was considered a major achievement and a benchmark for research and development both nationally and internationally. As a result, the new developments introduced in this project build on the foundations laid by the FEH and further improve the reliability of flood frequency estimation in the UK.

9.1 Improved modelling techniques

The model developments carried out in this project focused on three main aspects: i) improving the QMED equation, ii) revising the procedure for using data transfer from gauged donor sites to ungauged sites, and iii) the pooling procedure for estimation of growth curves at both gauged and ungauged sites. All three aspects of the method have been improved while retaining the general work-flow of the original FEH methodology.

Many of the improvements introduced through the development of the new QMED equation and the associated data transfer procedure are based on research carried out at CEH, particularly that of Kjeldsen and Jones (2006, 2007), identifying the linkage between the underlying structure and estimation of the QMED regression model and an optimal procedure for transfer of data from a gauged donor catchment to an ungauged subject catchment. In particular, this project has shown that identification of potential donor catchments should be based on geographical closeness rather than being based on ‘hydrological similarity’ as defined by catchment descriptors. Consequently, it is recommended that analogue catchments should no longer be used for adjusting QMED estimates obtained using the QMED equation. This is the case for both the existing FEH methodology and the new procedure introduced in this project. This is considered an important finding that should have significant influence on the current practical FEH procedures.

Through careful examination of the regression residuals from a number of potential QMED models, it was possible to identify a new QMED model that performs better than the FEH model while using only four catchment descriptors (compared to the six used in the FEH equation). The set of four catchment descriptors in the new equation is considered a more intuitive combination than that of the FEH equation and the project has managed to remove the RESHOST variable, which is not generally well-understood.

The revised procedure for estimation of the growth curve at ungauged sites using pooling-groups showed some improvements over the existing FEH procedure. However, the improvements were less significant than those observed in the QMED modelling part of the project. This is a result of the fundamental difficulty in flood frequency analysis that the higher order statistical moments of the flood series (L-CV and L-SKEW) that determine the growth curve have large sampling variances. They thus require longer series of observations than, for example, QMED to obtain reliable estimates of the true values. The high degree of sampling variability allows only weak relationships to be formed between the growth curves and catchment descriptors, hence the poor performance. The problem is illustrated by the fact that regression models linking L-CV and L-SKEW to catchment descriptors in FEH were found to have

r^2 values of 37.5 per cent and 8 per cent respectively, while the equivalent result for QMED was in the excess of 90 per cent.

Based on results from an extensive exploratory analysis the FEH definition of 'hydrological similarity' used for creating pooling groups was revised. The FEH definition of hydrological similarity was based on similarity of a subject site with regards to ln[AREA], ln[SAAR] and BFIHOST. The revised procedure presented in this report replaced BFIHOST with ln[FARL] and ln[FPEXT], while retaining ln[AREA] and ln[SAAR], as this combination of catchment descriptors was found to provide more accurate prediction of pooled growth curves at ungauged catchments (see Table 6.3). Also, see Section 9.2.6 for a further discussion of the problem of pooled frequency analysis on permeable catchments.

An important aspect of the improved methodology is the introduction of two separate weighting schemes for L-moment ratios within a pooling-group based on whether the pooling-group is formed for a gauged or an ungauged catchment. By first defining the statistical model underlying the pooling procedure (Appendix D), it was found that available at-site data should be given relatively more weight compared to the other sites in a pooling-group.

9.2 HiFlows-UK

Underlying the research presented in this report is the annual maximum peak flow data made available from the HiFlows-UK data project. The FEH recommends that POT data should be used for deriving estimates of QMED for short record lengths, where “short” is defined as less than 14 years of data. The initial review of the HiFlows-UK data found a number of practical issues with the updated POT dataset which could not reasonably be amended within this project. Consequently, POT data were not used in this study.

Compared to the dataset used in the development of the original FEH methodology, the extra quality control checks introduced in the HiFlows-UK project led to a reduction in the total number of gauged catchments used in the development of the method; specifically a reduction from 728 in the FEH to 602 in this study. However, the general increase in record length from an average of 22.7 years in the FEH to 32.7 years in this study ensured that the total number of AMAX events used in this study is 19 per cent greater than the number used in the FEH (see Table 2.1).

The extra quality control combined with the extended record length was reflected in the model development part of this study. In particular, the model diagnostics plots used for assessing the new QMED model clearly showed a better alignment between the regression model and the underlying data than that obtained in the development of the original FEH model. While the comparisons between the new and the FEH pooling procedures were undertaken based on HiFlows-UK data, the extended record lengths in HiFlows-UK will undoubtedly have a large effect on the estimated higher order L-moment ratios (L-CV and L-SKEW) by reducing their sampling variability. This allowed for a more robust pooling procedure to be developed, since a better relationship between the growth curves and the catchment descriptors could be identified, as reflected in the comparison between the methods (see Table 6.3).

9.3 Future direction of research and development

The objective of this project was to improve the existing statistical procedure outlined in the FEH Vol. 3. The current project has successfully achieved the following tasks.

- Improved the estimation of QMED from catchment descriptors.
- Provided a more robust method for data transfer from gauged to ungauged catchments.
- Provided an improved method to derive flood growth curves for both gauged and ungauged catchments using pooling groups.

However, the scope of this project did not encompass all aspects of the FEH methodology. Also, during the course of the project, particular parts of the methodology were identified where further research and development would be beneficial. This section provides a discussion of subjects where further research and development would provide further improvements of flood frequency estimation in the UK.

9.3.1 HiFlows-UK database

Given the importance of flood estimation to the UK in general terms, and given also the major role that the HiFlows-UK database plays in providing data for this task, there is a clear imperative to maintain and improve this resource. The FEH-based procedures have been constructed to enable good use to be made of any updates to the HiFlows-UK database, as soon as they are available.

Besides simply extending the records at the existing set of catchments included in HiFlows-UK, it is important to consider whether these catchments are sufficiently representative of catchments where flood estimation problems arise in practice. In particular, a view has been expressed by users of FEH methodology that they are often concerned with catchments that are rather smaller than those included in the HiFlows-UK data-set. Future research should pay particular attention to collection of hydrometric data and the performance of FEH methodologies on small catchments.

9.3.2 Flood peak data

While the HiFlows-UK database of AMAX events is a welcome development and while it has provided an improved dataset, it was regrettable that the general quality of the POT series was not found to be of a similar good quality. Flood frequency analysis based on AMAX series is a long established practice both in the UK and elsewhere. However, there are strong theoretical results that show that more reliable estimates of floods can be obtained when using statistical models developed for use with POT data. Furthermore, as the statistical models underlying the POT method are based on more mechanistic principles than the empirical distribution fitting used in AMAX modelling, POT models are more suitable for testing sensitivity of flood frequency to changes in flood-generating mechanisms. It is therefore recommended that research should be initiated to develop a national procedure for flood frequency estimation based on POT models. This would rely on there being a substantial improvement in the HiFlows-UK database regarding the details of the valid/invalid periods of the POT data records.

9.3.3 Flood frequency and environmental change

A very important aspect of flood frequency analysis in flood risk management is the potential effect of environmental change, such as urbanisation and climate change, on flood frequency characteristics. Traditionally, methods based on the statistical analysis of historical records have not been particularly well-suited for predicting the results of changes in the mechanisms which generate floods, and hence emphasis has been put on more conceptual hydrological models, such as the rainfall-runoff based approaches.

However, considering the relatively large amount of data underpinning the statistical method, it seems reasonable to develop empirical and robust measures for predicting the effect of environmental change as observed within the dataset. It is recommended that two particular aspects of environmental change of interest to flood managers should be further investigated.

Urbanisation

While the qualitative effect of increased urbanisation on flood response from a catchment is well understood (increase in the percentage runoff and decrease in the response time) the challenge in applied hydrology is to quantify these effects and to make a generally applicable model. Initial work on quantifying the effect of urbanisation using flood frequency models was reported by Packman (1980), which formed the basis for the procedure developed for the FEH statistical procedure. Later, Bayliss *et al.* (2006) updated the procedure to use $URBEXT_{2000}$ rather than $URBEXT_{1990}$ (as in the FEH) with some minor changes to the methodology as recommended by Morris (2003). To further improve the ability to predict the effect of urbanisation on the flood frequency characteristics for a particular catchment, it is necessary to undertake a critical review of the current adjustment procedures. In particular, the empirical adjustment factors should be formulated in a statistical framework to enable inference regarding the significance of any detected effects compared to the general variability observed in the flood peak data. Also, data characterising the temporal development of urbanisation should be collected and analysed for selected catchments, thereby providing detailed information on the effect of urbanisation on peak flow data. An excellent opportunity for research is provided by the HiFlows-UK database combined with measures of urbanisation derived from land cover maps such as $URBEXT_{1990}$, $URBEXT_{2000}$, and a potential new URBEXT measure based on new maps of land cover representing 2007.

Climate change

The current statistical method is based on assumptions of a stationary climate. The estimates from the method can, in some circumstances, be adjusted in order to make projections of the impacts of climate change. While it is generally accepted that climate change will have an impact on large-scale rainfall and runoff patterns, there is less certainty about the climate change signals detected from the analysis of observed time series of rainfall and runoff. In particular, little is known about the impact of climate change on extreme events. A comprehensive study investigating the existence of trends and shifts in the FEH dataset by Robson and Reed (1999) concluded that "*Climate change cannot be clearly detected in the FEH datasets*". However, since the publication of the FEH, the need for predicting and mitigating the potential effects of climate change has become of greater concern. Thus, despite weak signals of climate change being observed in historical flood data, research is urgently needed to i) identify the likely impact of climate change on the characteristics of future hydrological extremes and, ii) to develop a framework for estimating and reporting useful measures of the future probability of occurrence of extreme events. The specific activities that need to be undertaken are:

i) To refine and apply appropriate statistical tests for an exploratory investigation of change (trends, shifts and long-term periodic cycles) in long-term time series of observed river flow. An investigation should focus on the identification of temporal variability in both mean values and variability of observed time series. In particular, the study should seek to quantify changes in different seasons.

ii) Develop statistical extreme value models that can be applied in non-stationary environments, such as a changing climate. These models will allow for specification of identified and projected changes in the statistical properties of the extreme processes.

9.3.4 Catchment descriptors

The existing set of descriptors is probably as good as possible given the existing underlying datasets. They are wide-ranging in terms of types of properties being measured. One set of descriptors that might possibly be useful are quantities to measure diversity within a catchment. Of course, some of the existing measures do relate to diversity within the catchment, but other aspects such as soil and geology might be brought into consideration.

Possible improvements to the underlying data sources include the following.

- An improved HOST dataset, providing better quality data at a finer spatial resolution – but this would entail a recalibration of the HOST-derived quantities (BFIHOST, SPRHOST)
- An updated set of URBEXT descriptors might be based on the forthcoming land-cover map 2007.

There is also the possibility of making some minor improvements in the formulation of some of the existing catchment descriptors in an attempt to overcome some of the problems reported by Morris (2003) relating to how these vary when moving along a river channel.

9.3.5 Use of donor catchments

A very important improvement to the FEH procedure presented in this report is the revised procedure for estimation of QMED using data transfer from a gauged donor catchment to an ungauged subject catchment. While the new donor procedure is an important improvement, it is currently limited by allowing only one potential donor site to be used. Further model development and testing is necessary to allow more than one donor catchment to be used and to assess the effect of such a methodological extension.

Within the new framework for using donor catchments, this project initiated work on distinguishing between a donor catchment located on the same river network as the subject catchment and other donor catchments. More work is needed to further classify donor catchments according to location relative to donor catchments before such a system could be made operational. However, it would be an intuitive extension to the framework and could potentially add further improvements to the method.

9.3.6 Use of pooling-groups

The pooling-group method is a flexible tool allowing new and updated data to be used as they become available through HiFlows-UK. Consequently, the pooling-group method was retained in this project.

The improved method presented in this report distinguishes between a pooling-group formed for a gauged or an ungauged catchment and defines the weights given to the L-moment ratios for each catchment accordingly. Further model development could be undertaken to account for the intermediate case where a pooling-group is created for an ungauged catchment but data from a nearby gauged catchment are available.

These could be used in a manner similar to the donor transfer scheme defined for estimation of QMED at ungauged catchments. Further research would be needed to identify and quantify the underlying structure of the model errors arising from use of the pooling-group method.

As in the FEH, the formation of pooling-groups in the improved method is based on the the concept of hydrological similarity as defined by a set of catchment descriptors. However, the actual definition of hydrological similarity has been changed in this study, with the substitution of BFIHOST with FARL and FPEXT (retaining ln[AREA] and ln[SAAR]). This was a reasonable choice based on a thorough investigation of predictive ability of the catchment descriptors, but it does leave the method without any special attention being paid to growth curve estimation on permeable catchments -- the effect in FEH might have been largely illusory. It has been suggested that flood peak data from permeable catchment can exhibit what could be realisations from two distinct flood-generating mechanisms. It is recommended that further research should be undertaken to investigate the existence of such multiple mechanisms and, if confirmed, to determine how to incorporate such effects into the current procedures.

The use of pooling-groups (or regional methods in general) for enhancing single-site estimation is often referred to as “substituting space for time”. Among applied hydrologists there is a very reasonable attraction in trying to extend the flood data series extracted from systematic flow records back in time with more anecdotal evidence of large flood events that occurred before the systematic recordings were initiated and often pre-dating living memory. To support such activities, efforts have been made to compile and make available, through an on-line archive (http://www.dundee.ac.uk/geography/cbhe/), information on historical flood events on UK rivers (Black and Law, 2004). Unfortunately, these endeavours have not been matched by associated methodological developments for incorporating such information into flood frequency analyses based on data from systematic records. A further development of the existing FEH methodology would to combine both types of information in an overall flood frequency analysis. This would provide a significant development and effectively bring together long-standing efforts made by the gauging authorities, the British Hydrological Society, the academic community and a myriad of individuals to provide an improved methodology.

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Appendix A QMED values and gauge details

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
2001	Helmsdale	Kilphedir	284324	929794	28	1975	2002	06-Oct-1993	272.37	169.06	2001
2002	Brora	Bruachrobie	274462	916259	10	1993	2002	06-Dec-1999	205.49	143.55	2002
3002	Carron	Sgodachail	240482	888010	29	1974	2002	21-Feb-2002	342.78	184.24	3002
3003	Oykel	Easter Turnaig	231271	901365	25	1978	2002	05-Oct-1978	823.53	342.06	3003
4003	Alness	Alness	253141	877497	29	1974	2002	07-Oct-1993	252.97	82.21	4003
4005	Meig	Glenmeannie	220273	850353	18	1985	2002	16-Jan-1993	212.75	114.89	4005
4006	Bran	Dosmucheran	212722	856678	14	1989	2002	02-Jan-1992	120.8	85.16	4006
6003	Moriston	Invermoriston	221387	812362	14	1930	1943	20-Dec-1936	554.88	312.92	6003
6008	Enrick	Mill of Tore	238353	828104	24	1979	2002	01-Mar-1997	97.17	51.33	6008
7001	Findhorn	Shenachie	273215	821452	26	1977	2002	20-Sep-1981	485.52	268.21	7001
7002	Findhorn	Forres	284034	830206	45	1958	2002	16-Aug-1970	1112.63	312.01	7002
7003	Lossie	Sheriffmills	314502	853471	45	1958	2002	16-Nov-2002	151.35	43.43	7003
7004	Nairn	Firhall	273722	837368	22	1981	2002	01-Jul-1997	314.11	105.51	7004
7005	Divie	Dunphail	301689	839889	21	1982	2002	01-Jul-1997	141.65	60.44	7005
8001	Spey	Aberlour	292139	810489	62	1938	2002	17-Aug-1970	1179.31	415.62	8001
8002	Spey	Kinrara	270711	793742	52	1951	2002	18-Dec-1966	361.53	140.47	8002
8004	Avon	Delnashaugh	316609	817588	51	1952	2002	02-Oct-1981	521.3	221.37	8004
8005	Spey	Boat of Garten	275066	796799	52	1951	2002	18-Dec-1966	392.79	163.75	8005
8006	Spey	Boat o Brig	294879	812741	51	1952	2002	17-Aug-1970	1059	472.09	8006
8007	Spey	Invertruim	258191	791354	51	1952	2002	17-Dec-1966	274.68	100.81	8007
8008	Tromie	Tromie Bridge	276489	786784	51	1952	2002	06-Sep-1958	116.54	50.92	8008
8009	Dulnain	Balnaan Bridge	285086	819396	51	1952	2002	05-Feb-1990	172.26	94.4	8009
8010	Spey	Grantown	279940	802927	51	1952	2002	06-Feb-1990	507.15	223.91	8010
8011	Livet	Minmore	324546	823506	23	1980	2002	02-Oct-1981	51.82	31.04	8011
9001	Deveron	Avochie	344243	831607	44	1959	2002	15-Nov-2002	258.22	123.32	9001
9002	Deveron	Muiresk	348674	840599	44	1959	2002	12-Sep-1995	494.04	247.67	9002
9003	Isla	Grange	341980	850067	44	1959	2002	01-Jul-1997	96.07	46.41	9003
9004	Bogie	Redcraig	348530	829933	23	1980	2002	15-Nov-2002	95.61	27.43	9004
10001	Ythan	Ardlethen	381351	839185	46	1939	1984	06-Nov-1951	104.03	50.18	10001
10002	Ugie	Inverugie	396184	850658	32	1971	2002	23-Oct-2002	147.79	46.83	10002
10003	Ythan	Ellon	382301	837608	20	1983	2002	10-Feb-1996	105.26	63.85	10003
11001	Don	Parkhill	357673	817761	34	1969	2002	22-Nov-2002	454.27	138.51	11001
11002	Don	Haughton	348552	814053	32	1971	2002	22-Nov-2002	269.15	112.72	11002
11003	Don	Bridge of Alford	339397	812892	30	1973	2002	22-Nov-2002	206.91	97.84	11003
11004	Urie	Pitcaple	362209	828797	15	1988	2002	12-Sep-1995	59.73	25.02	11004
12001	Dee	Woodend	325598	793481	74	1929	2002	24-Jan-1937	1132.52	450.97	12001
12002	Dee	Park	335381	793266	30	1973	2002	22-Nov-2002	858.33	571.23	12002
12003	Dee	Polhollick	311368	790126	27	1976	2002	05-Feb-1990	484.8	302.95	12003
12005	Muick	Invermuick	330719	785799	26	1977	2002	21-Sep-1999	130.13	79.66	12005
12006	Gairn	Invergairn	325512	801212	25	1978	2002	13-Oct-1982	101.5	60.86	12006
12007	Dee	Mar Lodge	301326	789773	22	1981	2002	05-Feb-1990	312.69	191.25	12007
12008	Feugh	Heugh Head	360826	787475	18	1985	2002	07-Oct-1993	261.57	149.15	12008
13001	Bervie	Inverbervie	376480	778902	24	1979	2002	01-Dec-1985	67.7	37.68	13001

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
14001	Eden	Kemback	330237	711373	36	1967	2002	11-Feb-1977	68.95	41.49	14001
15003	Tay	Caputh	268182	753767	52	1951	2002	17-Jan-1993	1877.91	821.95	15003
15006	Tay	Ballathie	283585	754071	51	1952	2002	17-Jan-1993	2267.92	981.41	15006
15007	Tay	Pitnacree	259167	739905	52	1951	2002	17-Jan-1993	733.6	353.62	15007
15008	Dean Water	Cookston	341011	746580	50	1953	2002	11-Dec-1957	45.47	27.17	15008
15010	Isla	Wester Cardean	323994	760470	22	1972	1993	17-Jan-1993	158.81	85.02	15010
15013	Almond	Almondbank	288259	731392	30	1973	2002	16-Jan-1993	233.19	120.09	15013
15016	Tay	Kenmore	253572	733602	28	1975	2002	17-Jan-1993	336.11	189.48	15016
16001	Earn	Kinkell Bridge	275774	722833	55	1948	2002	16-Feb-1950	282.76	204.07	16001
16003	Ruchill Water	Cultybraggan	269860	716406	42	1960	2002	13-Jan-1975	225.46	145.24	16003
16004	Earn	Forteviot Bridge	280547	720580	30	1973	2002	17-Jan-1993	410.71	252.14	16004
17001	Carron	Headswood	273125	684424	34	1969	2002	15-Nov-1978	207.38	93.09	17001
19004	North Esk	Dalmore Weir	319829	657686	42	1961	2002	06-Oct-1990	53.99	19.96	19004
19008	South Esk	Prestonholm	331180	655398	26	1963	1988	03-Nov-1984	82.97	19.11	19008
19011	North Esk	Dalkeith Palace	321728	659964	41	1961	2002	26-Apr-2000	121.93	36.59	19011
20001	Tyne	East Linton	347341	666383	44	1959	2002	07-Nov-2000	160.64	59.85	20001
20002	West Peffer Burn	Luffness	352595	680164	38	1965	2002	04-Aug-1966	7.17	3.4	20002
20003	Tyne	Spilmersford	342842	663792	41	1962	2002	03-Nov-1984	132.45	34.17	20003
20005	Birns Water	Saltoun Hall	345090	662102	41	1962	2002	03-Nov-1984	54.44	18.69	20005
20007	Gifford Water	Lennoxlove	353773	665941	30	1973	2002	26-May-1983	75.82	18.87	20007
21001	Fruid Water	Fruid	310750	616956	15	1947	1961	15-Jan-1962	28.94	19.1	21001
21003	Tweed	Peebles	314086	636304	57	1939	2002	07-Jan-1949	426.96	174.93	21003
21005	Tweed	Lyne Ford	310348	629329	42	1961	2002	15-Jan-1962	226.61	123.49	21005
21007	Ettrick Water	Lindean	330137	621040	42	1961	2002	31-Oct-1977	456.47	237.64	21007
21008	Teviot	Ormiston Mill	356832	614437	43	1960	2002	22-Oct-2002	646.87	345.48	21008
21009	Tweed	Norham	352257	629303	43	1960	2002	04-Jan-1982	1511.46	772.69	21009
21011	Yarrow Water	Philiphaugh	327398	624661	19	1962	1980	31-Oct-1977	272.93	83.18	21011
21012	Teviot	Hawick	343049	607412	40	1963	2002	17-Feb-1997	295.95	188.39	21012
21013	Gala Water	Galashiels	341475	648495	40	1963	2002	03-Nov-1984	195.37	52.51	21013
21015	Leader Water	Earlston	353943	650943	37	1966	2002	03-Nov-1984	227.02	61.3	21015
21016	Eye Water	Eyemouth Mill	385382	663511	36	1967	2002	22-Oct-2002	114.74	37.52	21016
21017	Ettrick Water	Brockhoperig	320191	610867	38	1965	2002	30-Oct-1977	159.68	59.07	21017
21019	Manor Water	Cademuir	320823	631648	36	1967	2002	22-Oct-2002	50.43	26.13	21019
21020	Yarrow Water	Gordon Arms	322923	622849	14	1967	1980	30-Oct-1977	136.74	47.17	21020
21021	Tweed	Sprouston	340986	628413	33	1970	2002	04-Jan-1982	1452.09	770.77	21021
21022	Whiteadder Water	Hutton Castle	371489	657271	33	1970	2002	22-Oct-2002	316.85	133.9	21022
21024	Jed Water	Jedburgh	365676	610828	31	1972	2002	03-Nov-1984	142.89	66.11	21024
21025	Ale Water	Ancrum	347712	621531	30	1973	2002	22-Oct-2002	90.17	44.97	21025
21027	Blackadder Water	Mouth Bridge	371059	650492	29	1974	2002	22-Oct-2002	136.87	42.53	21027
21029	Tweed	Glenbreck	305784	617310	9	1964	1973	25-Sep-1965	47.71	37.76	21029
21030	Megget Water	Henderland	318923	622287	13	1969	1981	30-Oct-1977	117.56	77.67	21030
21031	Till	Etal	394992	625894	28	1955	1984	28-Aug-1956	299.61	82.9	21031
21032	Glen	Kirknewton	385595	625684	38	1961	2002	01-Apr-1992	117.48	43.28	21032
21034	Yarrow Water	Craig Douglas	321501	621791	13	1968	1980	31-Oct-1977	113.12	39.48	21034
22001	Coquet	Morwick	400758	603911	40	1963	2002	01-Apr-1992	365.71	137.38	22001
22002	Coquet	Bygate	383302	611166	15	1966	1980	12-Sep-1968	33.96	25.84	22002
22003	Usway Burn	Shillmoor	388728	614173	22	1966	2002	08-Sep-1995	54.58	17.14	22003
22004	Aln	Hawkhill	410419	614239	20	1960	1979	13-Aug-1966	150	63.23	22004

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
22006	Blyth	Hartford Bridge	411285	575860	43	1960	2002	07-Nov-2000	153.09	52.4	22006
22007	Wansbeck	Mitford	404914	587654	41	1962	2002	07-Mar-1963	395	100.42	22007
22009	Coquet	Rothbury	392511	606428	28	1973	2002	01-Apr-1992	265.73	131.49	22009
23001	Tyne	Bywell	378954	572789	47	1956	2002	17-Oct-1967	1496.93	870.79	23001
23002	Derwent	Eddys Bridge	396338	549462	11	1954	1964	28-Aug-1956	64.46	48.41	23002
23003	North Tyne	Reaverhill	377080	589424	20	1959	1978	23-Mar-1968	750.87	411.17	23003
23004	South Tyne	Haydon Bridge	373642	554530	44	1959	2002	31-Jan-1995	760.87	469.18	23004
23005	North Tyne	Tarset	365543	590723	19	1960	1978	30-Aug-1975	335.6	220.57	23005
23006	South Tyne	Featherstone	369209	547794	37	1966	2002	31-Jan-1995	384.07	236.7	23006
23007	Derwent	Rowlands Gill	402780	551182	38	1965	2002	06-Nov-2000	136.33	40.91	23007
23008	Rede	Rede Bridge	384095	596079	35	1968	2002	04-Jan-1982	266.62	131.19	23008
23009	South Tyne	Alston	371823	540057	25	1969	2002	30-Jul-2002	310.78	129.6	23009
23010	Tarset Burn	Greenhaugh	376212	592868	10	1970	1979	30-Aug-1975	105.63	63.97	23010
23011	Kielder Burn	Kielder	366671	598858	32	1970	2002	01-Feb-2002	106.84	64.63	23011
23012	East Allen	Wide Eals	383546	551702	11	1971	1981	25-Nov-1979	128.49	84.56	23012
23013	West Allen	Hindley Wrae	377486	551713	12	1971	1982	25-Nov-1979	127.15	53.83	23013
23015	North Tyne	Barrasford	377644	588998	22	1947	1969	02-Dec-1954	729.67	422.68	23015
24001	Wear	Sunderland Bridge	404825	534972	46	1957	2002	04-Jun-2000	375.69	185.08	24001
24003	Wear	Stanhope	388676	539354	45	1958	2002	31-Jan-1995	296.97	116.45	24003
24004	Bedburn Beck	Bedburn	405023	530533	43	1959	2002	04-Jun-2000	58.52	23.91	24004
24006	Rookhope Burn	Eastgate	391865	542746	20	1960	1979	11-Sep-1976	38.64	24.62	24006
24007	Browney	Lanchester	411164	544143	15	1968	1982	27-Dec-1978	21.93	10.98	24007
24008	Wear	Witton Park	398825	536850	29	1974	2002	31-Jan-1995	353.1	200.26	24008
25001	Tees	Broken Scar	396415	521254	47	1956	2002	26-Aug-1986	710.12	374.85	25001
25003	Trout Beck	Moor House	373799	531877	30	1962	2002	30-Jul-2002	44.63	15.16	25003
25005	Leven	Leven Bridge	453156	507565	43	1959	2002	03-Nov-2000	124.46	40.3	25005
25006	Greta	Rutherford Bridge	393998	510668	43	1960	2002	26-Aug-1986	210.33	73.78	25006
25008	Tees	Barnard Castle	388625	525152	39	1964	2002	25-Mar-1968	506.21	228.9	25008
25009	Tees	Low Moor	406923	520355	33	1969	2002	04-Jun-2000	581.55	375.79	25009
25011	Langdon Beck	Langdon	385506	533451	16	1969	2002	17-Jul-1983	35.02	15.38	25011
25012	Harwood Beck	Harwood	381653	533545	34	1969	2002	31-Jan-1995	63.76	31.24	25012
25018	Tees	Middleton in Teesdale	383018	529931	32	1971	2002	31-Jan-1995	388.79	186.59	25018
25019	Leven	Easby	460962	509663	25	1971	1995	11-Sep-1976	25.18	4.99	25019
26003	Foston Beck	Foston Mill	504662	465194	43	1959	2002	10-Feb-1977	2.95	1.72	26003
26802	Foston Beck	Foston Mill	488328	466463	4	1997	2002	06-Nov-2000	0.25	0.18	26802
26803	Foston Beck	Foston Mill	498435	463033	4	1998	2002	15-Nov-2000	1.01	0.77	26803
27002	Wharfe	Flint Mill Weir	408602	459310	67	1936	2002	15-Feb-1950	417.35	230.56	27002
27007	Ure	Westwick Lock	408676	481762	48	1955	2002	01-Feb-1995	517.6	276.61	27007
27008	Swale	Leckby Grange	422266	495156	29	1955	1983	07-Mar-1963	257.56	168.25	27008
27009	Ouse	Skelton	422906	481304	117	1886	2002	03-Nov-2000	583	312	27009
27010	Hodge Beck	Bransdale Weir	461816	498131	41	1936	1976	23-Jun-1946	31.03	9.42	27010
27014	Rye	Little Habton	463598	488603	15	1958	1972	05-Nov-1967	144.92	84.72	27014
27024	Swale	Richmond	397707	501071	20	1960	1979	23-Mar-1968	434.14	237.26	27024
27027	Wharfe	Ilkley	398527	466714	13	1960	1972	09-Dec-1965	424.03	267.21	27027
27034	Ure	Kilgram Bridge	396729	487690	36	1967	2002	01-Feb-1995	380.34	233.95	27034
27035	Aire	Kildwick Bridge	393465	455405	36	1967	2002	31-Oct-2000	163.35	66.42	27035
27038	Costa Beck	Gatehouses	478405	486210	32	1970	2002	15-Sep-1993	4.84	1.26	27038
27041	Derwent	Buttercrambe	476234	483445	30	1973	2002	09-Nov-2000	172.08	86.88	27041

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
27043	Wharfe	Addingham	398150	467369	30	1973	2002	03-Jan-1982	412.93	262.27	27043
27051	Crimple	Burn Bridge	426492	452134	31	1972	2002	01-Nov-2000	7.61	4.51	27051
27053	Nidd	Birstwith	411968	468699	27	1976	2002	31-Oct-2000	154.1	92.24	27053
27056	Pickering Beck	Ings Bridge	482273	491124	26	1977	2002	02-Aug-2002	40.77	14.41	27056
27059	Laver	Ripon	421740	473034	26	1977	2002	02-Nov-2000	62.68	22.01	27059
27084	Eastburn Beck	Crosshills	397155	443837	15	1988	2002	04-Jun-2000	50.66	25.66	27084
27086	Skell	Alma Weir	422502	471702	19	1984	2002	03-Nov-2000	76.49	27.56	27086
27087	Derwent	Low Marishes	493360	484721	14	1989	2002	10-Nov-2000	28.7	14.87	27087
27089	Wharfe	Tadcaster	410930	458204	12	1991	2002	01-Feb-1995	340.85	210.34	27089
27090	Swale	Catterick Bridge	401958	501699	10	1992	2001	31-Jan-1995	518.55	327.12	27090
27201	Swale	Catterick Bridge	395621	427036	13	1989	2001	04-Jun-2000	217.4	89.6	27201
28008	Dove	Rocester Weir	412867	354822	50	1953	2002	04-Dec-1960	138.54	88.17	28008
28011	Derwent	Matlock Bath	418165	376336	45	1958	2002	09-Dec-1965	407.93	113.92	28011
28018	Dove	Marston on Dove	408533	349064	42	1961	2002	06-Nov-2000	186.94	121.67	28018
28023	Wye	Ashford	411226	374534	37	1965	2002	27-Oct-1998	44.3	16.37	28023
28024	Wreake	Syston Mill	476502	316705	33	1969	2002	11-Apr-1998	129.3	39.54	28024
28031	Manifold	Ilam	407654	356758	35	1968	2002	23-Oct-1998	123.02	47.75	28031
28033	Dove	Hollinsclough	404552	368129	24	1966	2002	23-Oct-1998	18.71	4.65	28033
28041	Hamps	Waterhouses	405257	353971	18	1968	2002	10-Aug-1971	93.16	25.35	28041
28043	Derwent	Chatsworth	418886	383582	35	1968	2002	06-Nov-2000	204.25	78.95	28043
28046	Dove	Izaak Walton	411773	361404	33	1970	2002	21-Dec-1991	27.95	12.6	28046
28055	Ecclesbourne	Duffield	428768	349415	24	1971	2002	26-Jan-1995	30.54	13.61	28055
28058	Henmore Brook	Ashbourne	422849	349884	12	1974	1985	30-May-1979	21.45	13.88	28058
28061	Churnet	Basford Bridge	396765	356765	28	1975	2002	23-Aug-1987	66.71	27.46	28061
28070	Burbage Brook	Burbage	426299	382091	56	1925	1981	01-Jul-1958	27.85	4.3	28070
29001	Waithe Beck	Brigsley	520771	395873	43	1960	2002	26-Apr-1981	7.17	2.04	29001
29002	Great Eau	Claythorpe Mill	536273	377820	40	1963	2002	11-Jul-1968	13.3	3.25	29002
29003	Lud	Louth	529502	384953	37	1966	2002	02-Nov-1968	7.21	3.11	29003
29004	Ancholme	Bishopbridge	501036	386992	35	1968	2002	26-Apr-1981	22.6	6.15	29004
29009	Ancholme	Toft Newton	499618	385709	28	1974	2001	26-Apr-1981	7.07	1.83	29009
30003	Bain	Fulsby Lock	526134	376051	41	1962	2002	12-Oct-1993	39.53	16.3	30003
30004	Lymn	Partney Mill	534402	371019	41	1962	2002	26-Apr-1981	13.32	7.13	30004
30005	Witham	Saltersford total	490684	325074	35	1968	2002	09-Mar-1975	15.2	6.9	30005
30011	Bain	Goulceby Bridge	523650	386241	34	1966	2002	26-Apr-1981	16.34	2.52	30011
30014	Pointon Lode	Pointon	508244	329902	31	1972	2002	18-Jul-2001	12.9	2.56	30014
30017	Witham	Colsterworth	491229	320258	25	1978	2002	10-Apr-1998	20.22	5.92	30017
31004	Welland	Tallington	483677	298564	35	1967	2001	11-Apr-1998	94.54	37	31004
31005	Welland	Tixover	477726	293382	41	1962	2002	11-Apr-1998	79.41	37.74	31005
31010	Chater	Fosters Bridge	487563	303210	36	1967	2002	06-Nov-2000	27.33	10.32	31010
31023	West Glen	Easton Wood	495229	325297	31	1972	2002	14-Aug-1980	7.82	1.96	31023
31025	Gwash South Arm	Manton	482615	306835	25	1978	2002	02-Jun-1981	22.46	11.18	31025
32003	Harpers Brook	Old Mill Bridge	491255	284601	63	1938	2002	01-Mar-1993	52.84	9.93	32003
33005	Bedford Ouse	Thornborough Mill	467160	231972	28	1950	1977	01-Jan-1977	35.45	21.8	33005
33007	Nar	Marham	582917	315878	35	1968	2002	12-Feb-1977	7.88	3.69	33007
33011	Little Ouse	County Bridge Euston	599445	278215	42	1960	2002	05-Jan-2003	7.57	3.85	33011
33012	Kym	Meagre Farm	506371	265471	43	1960	2002	10-Apr-1998	30.28	14.5	33012
33013	Sapiston	Rectory Bridge	594868	268499	42	1960	2002	17-Sep-1968	15.6	5.41	33013
33018	Tove	Cappenham Bridge	463136	247958	39	1963	2002	09-Apr-1998	46.86	13.86	33018

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33019	Thet	Melford Bridge	599012	291010	43	1960	2002	29-Apr-1981	17.11	8.2	33019
33020	Alconbury Brook	Brampton	512089	276527	31	1963	1993	27-Apr-1981	16.27	12.52	33020
33021	Rhee	Burnt Mill	534753	244427	41	1962	2002	03-Jan-2003	13.43	9.18	33021
33027	Rhee	Wimpole	528835	243642	38	1965	2002	04-Feb-2001	9.26	5.58	33027
33029	Stringside	Whitebridge	573505	305835	38	1965	2002	10-Apr-1998	4.43	2.62	33029
33032	Heacham	Heacham	574858	333466	35	1966	2002	01-Aug-1980	1.2	0.47	33032
33034	Little Ouse	Abbey Heath	596477	281368	34	1967	2002	04-Jan-2003	31.41	17.93	33034
33037	Bedford Ouse	Newport Pagnell	470035	238160	34	1969	2002	10-Apr-1998	122	63.38	33037
33044	Thet	Bridgham	600029	291906	36	1967	2002	29-Aug-1987	15.85	7.98	33044
33045	Wittle	Quidenham	605154	287146	35	1967	2002	16-Sep-1968	3.4	1.17	33045
33046	Thet	Red Bridge	602298	295014	36	1967	2002	16-Sep-1968	17.52	8.05	33046
33049	Stanford Water	Buckenham Tofts	590032	295982	7	1966	1972	23-Sep-1968	4.14	0.79	33049
33051	Cam	Chesterford	551708	236036	34	1969	2002	07-Mar-1972	14.06	9.05	33051
33054	Babingley	Castle Rising	574758	325733	27	1976	2002	11-Feb-1977	2.14	1.13	33054
33055	Granta	Babraham	557649	246183	27	1976	2002	22-Oct-2001	20.41	4.11	33055
33057	Ouzel	Leighton Buzzard	493921	221073	22	1976	2002	12-Feb-2001	10.18	7.58	33057
33063	Little Ouse	Knettishall	601051	277607	23	1980	2002	27-Aug-1987	6.64	4.34	33063
34001	Yare	Colney	606922	304371	45	1958	2002	17-Sep-1968	21.8	7.98	34001
34003	Bure	Ingworth	613109	333025	44	1959	2002	27-Apr-1981	17.8	6.04	34003
34004	Wensum	Costessey Mill	597805	322666	34	1959	1998	15-Oct-1993	30.79	20.46	34004
34005	Tud	Costessey Park	605697	311919	42	1961	2002	27-Apr-1981	11.01	2.97	34005
34012	Burn	Burnham Overy	584689	337532	37	1966	2002	28-Jun-2002	2.84	0.99	34012
35008	Gipping	Stowmarket	601946	259639	37	1964	2002	02-Feb-1979	34	12.18	35008
36002	Glem	Glemsford	578966	252844	40	1963	2002	15-Sep-1968	23	8.17	36002
36003	Box	Polstead	593948	242065	40	1963	2002	22-Nov-1974	13.26	3.84	36003
36004	Chad Brook	Long Melford	586647	250956	36	1967	2002	15-Sep-1968	22.47	5.4	36004
36005	Brett	Hadleigh	596377	249596	39	1963	2002	11-Oct-1987	31.35	11.56	36005
36006	Stour	Langham	579555	245068	40	1963	2002	17-Sep-1968	90	29.51	36006
36007	Belchamp Brook	Bardfield Bridge	581018	240358	39	1964	2002	21-Oct-2001	15.33	4.63	36007
36008	Stour	Westmill	569913	247315	43	1960	2002	16-Sep-1968	85	18.95	36008
36009	Brett	Cockfield	590503	255182	33	1967	2002	21-Oct-2001	6.05	4.12	36009
36010	Bumpstead Brook	Broad Green	565863	241222	36	1967	2002	21-Oct-2001	27.75	6.87	36010
36012	Stour	Kedington	567272	251505	36	1967	2002	19-Sep-1968	29.13	12.78	36012
36015	Stour	Lamarsh	576876	247076	30	1973	2002	11-Oct-1987	40.13	31.69	36015
37003	Ter	Crabbs Bridge	573430	217809	40	1963	2003	21-Oct-2001	8.89	4.88	37003
37005	Colne	Lexden	581429	232555	43	1960	2002	22-Oct-2001	31.45	12.42	37005
37010	Blackwater	Appleford Bridge	575177	227559	41	1962	2002	22-Oct-2001	29.22	11.3	37010
37011	Chelmer	Churchend	560093	228787	40	1963	2002	21-Oct-2001	22.35	9.74	37011
37012	Colne	Poolstreet	572778	237726	39	1964	2002	16-Sep-1968	22.5	8.86	37012
37013	Sandon Brook	Sandon Bridge	575428	201211	37	1963	2002	08-Feb-2001	16.77	7.53	37013
37014	Roding	High Ongar	558197	213815	40	1963	2002	31-Oct-2000	19.5	11.15	37014
37016	Pant	Copford Hall	562345	235668	38	1965	2002	21-Oct-2001	21.35	8.92	37016
37017	Blackwater	Stisted	567758	232355	34	1969	2002	22-Oct-2001	29.82	13.8	37017
37020	Chelmer	Felsted	562293	226088	33	1970	2002	22-Oct-2001	19.63	13.46	37020
38002	Ash	Mardock	543206	222683	62	1939	2002	22-Oct-2001	19.09	6.76	38002
38004	Rib	Wadesmill	537728	228623	44	1959	2002	16-Sep-1968	42.5	12.14	38004
38026	Pincey Brook	Sheering Hall	554007	216705	29	1974	2002	30-Oct-2000	19.79	11.08	38026
39002	Thames	Days Weir	430925	212889	65	1938	2002	17-Mar-1947	349.19	149.59	39002

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39006	Windrush	Newbridge	418884	219840	53	1950	2002	04-Jan-2003	22.52	11.3	39006
39008	Thames	Eynsham	414913	204780	12	1991	2002	05-Jan-2003	91.8	78.05	39008
39016	Kennet	Theale	433673	170432	42	1961	2002	11-Jun-1971	71	38.5	39016
39018	Kennet	Theale	437749	192940	16	1962	1977	06-Mar-1972	15.8	10.45	39018
39019	Lambourn	Shaw	437599	178291	41	1962	2002	19-Dec-2000	6.74	3.55	39019
39020	Coln	Bibury	405568	216076	40	1963	2002	15-Dec-2000	6.49	3.75	39020
39025	Enborne	Brimpton	448699	160992	36	1967	2002	30-Oct-2000	32.28	17.14	39025
39026	Cherwell	Banbury	449514	249775	36	1966	2002	10-Apr-1998	90.85	16.02	39026
39028	Dun	Hungerford	425985	164944	35	1968	2002	01-Jan-2003	3.92	2.39	39028
39029	Tillingbourne	Shalford	508055	146327	36	1967	2002	15-Sep-1968	6.09	2.02	39029
39034	Evenlode	Cassington Mill	432691	223000	35	1970	2004	28-Dec-1979	26.7	20.4	39034
39035	Churn	Cerney Wick	400043	209009	34	1969	2002	31-Jan-1971	4.76	3.53	39035
39036	Law Brook	Albury	507366	144917	36	1967	2002	06-Nov-2000	0.82	0.46	39036
39037	Kennet	Marlborough	410751	170291	31	1972	2002	02-Jan-2003	23.82	3.07	39037
39042	Leach	Priory Mill Lechlade	415948	209471	31	1972	2002	15-Dec-2000	5.65	3.54	39042
39081	Ock	Abingdon	437189	192523	24	1979	2002	03-Jan-2003	23.8	10.66	39081
40004	Rother	Udiam	566051	125058	39	1962	2002	12-Oct-2000	65.73	39.29	40004
40005	Beult	Stile Bridge	585642	142131	42	1958	2000	13-Oct-2000	101.82	42.1	40005
40009	Teise	Stone Bridge	566350	135405	27	1975	2002	12-Oct-2000	104.39	26.9	40009
41003	Cuckmere	Sherman Bridge	556551	114104	42	1959	2002	25-Nov-1982	144.87	39.69	41003
41005	Ouse	Gold Bridge	535445	127422	42	1960	2002	12-Oct-2000	94.44	32.54	41005
41011	Rother	Iping Mill	477884	125009	36	1967	2002	16-Sep-1968	114.69	27.6	41011
41014	Arun	Pallingham Quay	507351	132316	29	1973	2002	28-Dec-1979	149.05	76.9	41014
41015	Ems	Westbourne	478470	113230	36	1967	2002	09-Dec-2000	6.78	1.95	41015
41016	Cuckmere	Cowbeech	560883	118771	36	1967	2002	12-Oct-2000	27.7	13.71	41016
41018	Kird	Tanyards	498540	128368	32	1969	2000	04-Jan-2001	59.62	19.9	41018
41020	Bevern Stream	Clappers Bridge	536753	115688	34	1969	2002	12-Oct-2000	33.6	13.57	41020
41022	Lod	Halfway Bridge	491432	126898	30	1973	2002	27-Dec-1979	41.5	17.14	41022
41023	Lavant	Graylingwell	487719	113373	27	1971	2002	14-Dec-2000	7.83	1.47	41023
41025	Loxwood Stream	Drungewick	498040	134412	30	1973	2002	04-Mar-1997	68.08	30.96	41025
41028	Chess Stream	Chess Bridge	525651	115288	39	1964	2002	21-Nov-1974	14.26	6.83	41028
42003	Lymington	Brockenhurst	426184	105415	21	1982	2002	25-Dec-1999	62.15	21.19	42003
42005	Wallop Brook	Broughton	428891	137030	40	1955	2002	13-Dec-2000	5.02	1.12	42005
42006	Meon	Mislingford	463826	120638	44	1958	2002	13-Dec-2000	11	2.89	42006
42008	Cheriton Stream	Sewards Bridge	461728	127314	33	1970	2002	13-Dec-2000	4.96	1.3	42008
42009	Candover Stream	Borough Bridge	460963	141287	32	1971	2002	10-Dec-2000	4.44	1.02	42009
42010	Itchen	Highbridge+Allbrook	457279	132838	45	1958	2002	13-Dec-2000	20.5	9.31	42010
42011	Hamble	Frogmill	456316	119165	31	1972	2002	05-Nov-2000	12.94	7.93	42011
42014	Blackwater	Ower	426272	120791	27	1976	2002	25-Dec-1999	30.58	14.74	42014
43003	Avon	East Mills	405962	140935	32	1965	2002	11-Mar-1967	81.73	46.98	43003
43004	Bourne	Laverstock	421744	146232	32	1964	2002	03-Jan-2003	7.96	2.26	43004
43005	Avon	Amesbury	413152	155342	38	1965	2002	03-Jan-2003	28.19	11.11	43005
43006	Nadder	Wilton	395753	129698	36	1966	2002	28-Dec-1979	47.88	16.45	43006
43007	Stour	Throop	385102	113186	30	1973	2002	28-Dec-1979	292.52	113.71	43007
43008	Wylye	South Newton	396257	142669	32	1966	2002	02-Feb-1995	29.77	12.97	43008
43009	Stour	Hammoon	376203	119594	35	1968	2002	27-Dec-1979	236.57	120.53	43009
43010	Allen	Loverley Mill	398756	115822	22	1971	2002	15-Dec-2000	7.42	3.82	43010
43012	Wylye	Norton Bavant	385023	140062	34	1969	2002	07-Mar-1990	7.26	4.69	43012

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
43014	East Avon	Upavon	416333	160687	32	1970	2002	30-Oct-2000	6.35	3.79	43014
43017	West Avon	Upavon	406844	160525	33	1970	2002	01-Oct-1989	11	5.6	43017
43018	Allen	Walford Mill	398328	111954	29	1974	2002	13-Dec-2000	17.28	7.33	43018
43019	Shreen Water	Colesbrook	380592	131883	30	1973	2002	30-Oct-2000	22.85	13.53	43019
43801	Shreen Water	Colesbrook	396070	147184	8	1994	2002	13-Dec-2000	8.59	5.68	43801
43806	Shreen Water	Colesbrook	382845	136388	12	1991	2002	14-Nov-2002	4.3	2.86	43806
44001	Frome	East Stoke Total	367872	93022	11	1992	2002	30-Dec-1993	29.66	23.87	44001
44002	Piddle	Baggs Mill	377762	97463	38	1965	2002	08-Jan-1968	11.86	8.27	44002
44003	Asker	Bridport	351377	95390	21	1966	2002	05-Nov-2000	35.25	12.5	44003
44004	Frome	Dorchester Total	361401	98017	33	1969	2002	27-Dec-1979	23.13	16.05	44004
44006	Sydling Water	Sydling St Nicholas	362829	101665	29	1969	2002	31-Dec-2000	1.65	0.9	44006
44008	Sth Winterbourne	W'bourne Steepleton	359404	90873	12	1991	2002	01-Jan-2003	1.99	0.37	44008
44801	Sth Winterbourne	W'bourne Steepleton	352000	101792	11	1992	2002	01-Jan-2003	2.51	1.23	44801
44807	Sth Winterbourne	W'bourne Steepleton	379332	82697	4	1999	2002	24-Oct-1999	1.85	1.47	44807
44810	Sth Winterbourne	W'bourne Steepleton	373980	98698	10	1993	2002	13-Dec-2000	12.02	9.33	44810
45001	Exe	Thorverton	291198	125205	47	1956	2002	04-Dec-1960	492.57	166.42	45001
45002	Exe	Stoodleigh	289667	130913	43	1960	2002	04-Dec-1960	331.33	144.93	45002
45003	Culm	Wood Mill	308880	111882	41	1962	2002	11-Jul-1968	201.21	72.08	45003
45004	Axe	Whitford	332345	104570	39	1964	2002	11-Jul-1968	251.76	103.23	45004
45005	Otter	Dotton	313401	101018	41	1962	2002	11-Jul-1968	346.71	70.9	45005
45008	Otter	Fenny Bridges	317423	105040	29	1974	2002	07-Dec-2000	184.32	53.3	45008
45009	Exe	Pixton	291729	134753	37	1966	2002	30-Oct-2000	70.18	46.31	45009
45012	Creedy	Cowley	281643	100832	39	1964	2002	08-Dec-2000	196.02	78.37	45012
45013	Tale	Fairmile	308981	102297	24	1978	2002	30-Dec-1981	19.56	9.89	45013
45816	Tale	Fairmile	300160	130640	10	1993	2002	29-May-1999	13.13	4.11	45816
45817	Tale	Fairmile	299063	130043	10	1993	2002	29-May-1999	3.58	1.45	45817
45818	Tale	Fairmile	299130	134000	11	1992	2002	29-May-1999	12.99	4.34	45818
45819	Tale	Fairmile	262294	139416	36	1967	2002	30-Oct-2000	49.99	14.06	45819
46003	Dart	Austins Bridge	267325	74040	45	1958	2002	27-Dec-1979	496.58	234.38	46003
46005	East Dart	Bellever	263051	81181	39	1964	2002	27-Dec-1979	60.66	37.56	46005
46007	West Dart	Dunnabridge	260714	76572	22	1972	2002	27-Dec-1979	131.85	73.24	46007
46008	Avon	Loddiswell	270511	57787	23	1971	2002	27-Dec-1979	88.95	67.24	46008
47001	Tamar	Gunnislake	234596	90512	47	1956	2002	28-Dec-1979	714.19	268.47	47001
47004	Lynher	Pillaton Mill	229409	72589	42	1961	2002	28-Dec-1979	106.99	48.19	47004
47005	Ottery	Werrington Park	223677	91033	39	1961	2002	27-Dec-1979	109.77	65.12	47005
47006	Lyd	Lifton Park	246584	88524	19	1962	1980	04-Nov-1967	274.67	94.74	47006
47007	Yealm	Puslinch	260299	57994	41	1962	2002	28-Nov-1965	26.79	22.46	47007
47008	Thrushel	Tinhay	245181	91620	19	1969	1987	27-Dec-1979	125.26	46.67	47008
47009	Tiddy	Tideford	231066	64366	34	1969	2002	20-Jan-1999	10.45	6.21	47009
47010	Tamar	Crowford Bridge	228557	108393	31	1972	2002	19-Dec-1999	22.73	16.55	47010
47011	Plym	Carn Wood	256358	66809	14	1971	2002	27-Dec-1979	116.97	48.01	47011
47013	Withey Brook	Bastreet	223310	75487	31	1972	2002	18-Dec-1999	24.17	11.95	47013
47014	Walkham	Horrabridge	254962	73828	30	1973	2002	27-Dec-1979	73.57	30.27	47014
47015	Tavy	Denham / Ludbrook	251815	76692	22	1981	2002	31-Dec-2000	283.92	109.03	47015
47018	Thrushel	Hayne Bridge	247809	91097	15	1988	2002	30-Oct-2000	41.69	30.5	47018
47020	Inny	Beals Mill	224015	81813	21	1976	2002	19-Dec-1999	55.3	32.62	47020
47804	Inny	Beals Mill	242967	95441	11	1992	2002	18-Dec-1999	15.51	7.63	47804
47805	Inny	Beals Mill	245919	95770	12	1991	2002	07-Dec-1994	51.29	14.34	47805

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
48001	Fowey	Trekeivesteps	220765	74772	34	1969	2002	18-Dec-1999	43.2	16.97	48001
48003	Fal	Tregony	194928	54536	40	1961	2002	28-Dec-1979	22.93	12	48003
48004	Warleggan	Trengoffe	215277	71462	34	1969	2002	27-Dec-1979	23.64	8.91	48004
48006	Cober	Helston	167298	32352	21	1968	1988	28-Dec-1979	11.94	5.53	48006
48007	Kennal	Ponsanooth	172159	36762	35	1968	2002	01-Jan-2003	7.97	4.08	48007
48009	St Neot	Craigshill Wood	218187	71271	12	1971	1982	27-Dec-1979	21.11	8.47	48009
48010	Seaton	Trebrownbridge	227802	64417	31	1972	2002	20-Jan-1999	15.06	6.96	48010
48011	Fowey	Restormel	216553	69916	18	1985	2002	19-Dec-1999	108.08	46.54	48011
48801	Fowey	Restormel	168391	33697	16	1987	2002	28-Jan-1988	7.48	2.86	48801
48802	Fowey	Restormel	174808	42128	9	1991	1999	18-Dec-1999	19.67	9.77	48802
48803	Fowey	Restormel	173849	42260	9	1994	2002	01-Jan-2003	10.22	5.51	48803
49001	Camel	Denby	207824	73231	39	1964	2002	12-Jun-1993	306.4	71.15	49001
49002	Hayle	St Erth	159925	32469	46	1957	2002	01-Jan-1963	15	4.4	49002
49003	De Lank	De Lank	215420	78115	37	1966	2002	21-Sep-1980	36.44	12.93	49003
49004	Gannel	Gwills	186166	57381	34	1969	2002	07-Dec-2000	27.39	13.65	49004
50001	Taw	Umberleigh	272169	117345	45	1958	2002	30-Oct-2000	618.24	222.45	50001
50002	Torridge	Torrington	248590	107223	42	1960	2002	28-Dec-1979	516.58	230.04	50002
50005	West Okement	Vellake	258022	87659	36	1967	2002	17-May-1971	53.17	21.32	50005
50006	Mole	Woodleigh	274173	128743	38	1965	2002	31-Oct-1998	189.85	112.28	50006
50007	Taw	Taw Bridge	264734	97339	30	1973	2002	30-Oct-2000	50.52	29.7	50007
50008	Lew	Gribbleford Bridge	250125	98332	15	1988	2002	18-Dec-1999	110.34	59.64	50008
50009	Lew	Norley Bridge	247497	98926	15	1988	2002	18-Dec-1999	24.68	18.89	50009
50010	Torridge	Rockhay Bridge	238420	112315	15	1988	2002	19-Dec-1999	124.71	102.61	50010
50011	Okement	Jacobstowe	258914	93284	20	1973	2002	27-Dec-1979	169.99	59.18	50011
50012	Yeo	Veraby	282141	128002	33	1968	2002	31-Oct-1998	25.23	19.11	50012
50801	Yeo	Parkham	237300	122071	32	1969	2002	27-Dec-1979	9.44	5.98	50801
51001	Doniford Stream	Swill Bridge	309710	137415	37	1966	2002	10-Jul-1968	56.9	12.25	51001
51002	Horner Water	West Luccombe	287466	143161	22	1973	2002	30-Oct-2000	40.8	11.6	51002
51003	Washford	Beggearn Huish	300447	136965	36	1966	2002	26-May-1983	27.38	6.8	51003
52003	Halsewater	Halsewater	315396	130295	42	1961	2002	09-Feb-1974	17.81	12.24	52003
52004	Isle	Ashford Mill	334328	113224	40	1962	2002	30-Oct-2000	39.9	27.19	52004
52005	Tone	Bishops Hull	310309	124174	42	1961	2002	30-Oct-2000	79.69	43.72	52005
52006	Yeo	Pen Mill	359794	112721	41	1962	2002	15-Feb-1963	149.82	50.31	52006
52007	Parrett	Chiselborough	347217	110232	37	1966	2002	30-May-1979	173.1	31.35	52007
52010	Brue	Lovington	367131	135772	39	1964	2002	30-May-1979	141.57	36.28	52010
52011	Cary	Somerton	355533	128169	38	1965	2002	01-Jun-1979	13.66	9.62	52011
52014	Tone	Greenham	304516	127449	37	1966	2002	07-Dec-2000	26.75	13.62	52014
52015	Land Yeo	Wraxall Bridge	351546	169292	24	1970	2002	16-Jul-1994	7.61	3.38	52015
52016	Currypool Stream	Currypool Farm	318469	137311	33	1970	2002	01-Dec-1976	7.7	2.67	52016
52025	Hillfarrance	Milverton	308310	128522	11	1992	2002	07-Dec-2000	11.34	7.63	52025
53002	Semington Brook	Semington	397337	157744	27	1973	2002	14-Feb-1974	19.34	14.18	53002
53004	Chew	Compton Dando	357940	160244	44	1958	2002	10-Jul-1968	226.48	18.83	53004
53007	Frome(Somerset)	Tellisford	373521	146516	42	1961	2002	11-Jul-1968	113.24	57.87	53007
53008	Avon	Great Somerford	388259	186712	40	1963	2002	11-Jul-1968	108.25	36.74	53008
53013	Marden	Stanley	401470	172405	34	1969	2002	30-Oct-2000	43.31	15.38	53013
53017	Boyd	Bitton	371777	175065	30	1973	2002	30-May-1979	27.67	12.83	53017
53018	Avon	Bathford	385923	166414	34	1969	2002	30-Oct-2000	272.66	171.2	53018
53025	Mells	Vallis	367966	146969	24	1979	2002	07-Oct-1993	40.27	21.54	53025

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
53028	By Brook	Middlehill	380982	174546	22	1981	2002	02-Jan-2003	13.78	10.69	53028
54001	Severn	Bewdley	336743	309876	80	1923	2002	21-Mar-1947	533.48	330.72	54001
54005	Severn	Montford	310947	306938	50	1952	2002	01-Nov-2000	473.42	284.16	54005
54008	Teme	Tenbury	340470	281430	47	1956	2002	03-Dec-1960	240.6	139.08	54008
54012	Tern	Walcot	363754	325596	44	1959	2002	29-Jan-1990	60.02	37.6	54012
54014	Severn	Abermule	300201	289855	43	1960	2002	05-Dec-1960	581.41	191.49	54014
54016	Roden	Rodington	351699	328761	42	1961	2002	03-Jul-1968	28.15	14.41	54016
54018	Rea Brook	Hookagate	336296	305670	41	1962	2002	06-Nov-2000	45.11	22.65	54018
54020	Perry	Yeaton	337381	328873	40	1963	2002	08-Feb-1990	17.65	10.74	54020
54022	Severn	Plynlimon flume	283246	288071	52	1951	2002	15-Aug-1977	32.22	13.77	54022
54025	Dulas	Rhos-y-pentref	296856	278995	34	1969	2002	27-Oct-1998	46.94	23.16	54025
54028	Vyrnwy	Llanymynech	307738	318661	33	1969	2002	11-Feb-2002	486.37	267.42	54028
54029	Teme	Knightsford Bridge	346634	279096	33	1970	2002	28-Dec-1979	247.04	168.47	54029
54034	Dowles Brook	Oak Cottage	372015	276775	32	1971	2002	10-Jun-1993	21.59	9.55	54034
54036	Isbourne	Hinton on the Green	403964	231915	30	1972	2002	09-Apr-1998	37.97	13.99	54036
54038	Tanat	Llanyblodwel	312711	327199	31	1972	2002	06-Nov-2000	152.09	77.14	54038
54040	Meese	Tibberton	375818	322857	30	1973	2002	06-Nov-2000	9.58	5.02	54040
54041	Tern	Eaton On Tern	367078	333733	31	1972	2002	07-Nov-2000	23.07	11.11	54041
54044	Tern	Ternhill	372032	336285	31	1972	2002	06-Nov-2000	18.41	4.85	54044
54102	Avon	Lilbourne	462407	279063	24	1974	2002	09-Apr-1998	33.15	16.46	54102
54106	Stour	Shipston	424857	236671	17	1986	2002	09-Apr-1998	91.34	20.74	54106
55002	Wye	Belmont	306152	255938	95	1908	2002	28-Oct-1998	607.77	380.8	55002
55003	Lugg	Lugwardine	338685	257804	33	1964	2002	04-Feb-2002	60.86	44.48	55003
55004	Irfon	Abernant	284965	252743	45	1937	1981	06-Aug-1973	120.41	56.54	55004
55005	Wye	Rhayader	291753	277164	31	1938	1968	13-Dec-1964	279.13	115.32	55005
55007	Wye	Erwood	298496	263086	64	1938	2002	02-Dec-1960	1228.83	556.22	55007
55011	Ithon	Llandewi	309350	277914	15	1959	1980	03-Dec-1960	74	53.51	55011
55012	Irfon	Cilmery	289393	250197	35	1966	2002	23-Oct-1998	397.74	170.27	55012
55013	Arrow	Titley Mill	323594	254543	35	1966	2002	10-Jan-1986	57.66	27.25	55013
55014	Lugg	Byton	324892	265277	35	1966	2002	28-Oct-1998	86.85	30.05	55014
55021	Lugg	Butts Bridge	334076	264541	32	1969	2002	28-Jan-1990	64.7	44.81	55021
55022	Trothy	Mitchel Troy	341042	214581	25	1970	2002	27-Dec-1979	49.1	38.28	55022
55023	Wye	Redbrook	326244	248366	33	1969	2002	03-Feb-2002	904.38	530.02	55023
55025	Llynfi	Three Cocks	312742	232028	32	1970	2002	27-Dec-1979	198.42	48	55025
55026	Wye	Ddol Farm	292074	276803	33	1969	2001	06-Aug-1973	215.51	114.79	55026
55029	Monnow	Grosmont	334942	231598	30	1973	2002	09-Apr-1998	221.91	157.37	55029
56001	Usk	Chain Bridge	308051	225004	46	1957	2002	27-Dec-1979	945	387.19	56001
56003	Honddu	The Forge Brecon	302453	237135	21	1963	1983	27-Dec-1979	73.04	23.46	56003
56004	Usk	Llandetty	297278	229567	38	1965	2002	27-Dec-1979	774.24	328.63	56004
56006	Usk	Trallong	288960	227656	38	1963	2002	23-Oct-1998	383.99	155.41	56006
56007	Senni	Pont Hen Hafod	292742	221883	35	1968	2002	22-Oct-1998	53.13	27.46	56007
56013	Yscir	Pontaryscir	297621	238443	31	1972	2002	06-Oct-1985	96.01	35.81	56013
57015	Taff	Merthyr Tydfil	302335	214033	25	1978	2002	27-Dec-1979	313.3	93.56	57015
58002	Neath	Resolven	290201	210206	42	1960	2002	16-Oct-1967	411.25	197.03	58002
58006	Mellte	Pontneddfechan	294644	214977	32	1971	2002	23-Oct-1998	176.12	89.2	58006
58010	Hepste	Esgair Carnau	297141	216070	18	1975	2001	22-Oct-1998	17.18	12.52	58010
58012	Afan	Marcroft Weir	284377	196842	25	1978	2002	27-Dec-1979	176.79	101.74	58012
59001	Tawe	Ynystanglws	277704	212026	38	1957	2002	23-Oct-1998	456.58	258.47	59001

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59002	Loughor	Tir-y-dail	261859	216026	36	1967	2002	26-Dec-1979	130	64.85	59002
60001	Loughor	Tir-y-dail	269002	235626	29	1958	2002	27-Dec-1979	827.74	360.98	60001
60002	Cothi	Felin Mynachdy	260063	237727	43	1960	2002	18-Oct-1987	498.42	156.66	60002
60003	Taf	Clog-y-Fran	218991	222325	39	1964	2002	25-Aug-1986	86.39	59.77	60003
60005	Bran	Llandovery	281412	241032	6	1997	2002	23-Oct-1998	51.5	41.05	60005
60006	Gwili	Glangwili	240908	229292	35	1968	2002	24-Oct-1998	197.46	91.15	60006
60010	Tywi	Nantgaredig	268978	235608	45	1958	2002	19-Oct-1987	890.79	308.84	60010
60013	Cothi	Pont Ynys Brechfa	262036	239779	10	1971	1980	27-Dec-1979	244.1	122.9	60013
61001	Western Cleddau	Prendergast Mill	195048	226904	42	1961	2002	18-Oct-1987	127.12	51.81	61001
61002	Eastern Cleddau	Canaston Bridge	208851	224685	44	1959	2002	25-Aug-1986	143.21	85.97	61002
62001	Teifi	Glan Teifi	248986	248171	44	1959	2002	19-Oct-1987	448.83	203.2	62001
62002	Teifi	Llanfair	259932	253698	12	1971	1982	27-Dec-1979	252.51	124.98	62002
63001	Ystwyth	Pont Llolwyn	271615	274267	42	1961	2002	12-Dec-1964	153.06	91.88	63001
63002	Rheidol	Llanbadarn Fawr	274413	283210	28	1963	2002	29-Jun-2001	468.44	95.06	63002
64001	Dyfi	Dyfi Bridge	284140	306844	41	1962	2002	06-Aug-1973	405.74	309	64001
64002	Dysynni	Pont-y-Garth	269100	309379	36	1967	2002	30-Oct-2000	67.13	43.66	64002
65001	Glaslyn	Beddgelert	261419	351185	36	1967	2002	19-Dec-1993	140.78	88.99	65001
65004	Gwyrfai	Bontnewydd	255039	356469	32	1971	2002	21-Mar-1981	46.51	20.94	65004
65005	Erch	Pencaenewydd	239274	343245	31	1972	2002	21-Aug-2000	63.39	10.85	65005
65006	Seiont	Peblig Mill	257847	360309	27	1975	2002	18-Oct-1987	67.06	41.72	65006
65007	Dwyfawr	Garndolbenmaen	253671	345658	29	1974	2002	18-Oct-1987	81.51	38.84	65007
66001	Clwyd	Pont-y-Cambwll	309229	360668	30	1973	2002	06-Nov-2000	90.92	46.22	66001
66002	Elwy	Pant yr Onen	291474	365507	12	1961	1972	12-Dec-1964	152.65	65.6	66002
66004	Wheeler	Bodfari	315144	371478	29	1974	2002	06-Nov-2000	6.71	3.46	66004
66005	Clwyd	Ruthin Weir	309816	351808	27	1972	2002	06-Nov-2000	21.12	14.23	66005
66006	Elwy	Pont-y-Gwyddel	290505	364668	29	1974	2002	14-Oct-1976	142.31	67.4	66006
66011	Conwy	Cwm Llanerch	278217	352151	38	1964	2002	11-Feb-2002	499.96	377.02	66011
67003	Brenig	Llyn Brenig outflow	297273	356836	10	1964	1973	31-Jul-1972	28.82	15.28	67003
67005	Ceiriog	Brynkinalt Weir	317503	336107	45	1952	2002	06-Nov-2000	66.82	29.92	67005
67006	Alwen	Druid	296649	349512	43	1960	2002	12-Dec-1964	187.97	72.38	67006
67008	Alyn	Pont-y-Capel	323018	359064	38	1965	2002	07-Nov-2000	58.93	22.15	67008
67009	Alyn	Rhydymwyn	319019	357784	47	1956	2002	06-Nov-2000	36.33	8.62	67009
67010	Gelyn	Cynefail	283514	343508	30	1966	2002	03-Jul-2001	30.08	16.36	67010
67013	Hirnant	Plas Rhiwedog	296006	331068	12	1967	1978	19-Oct-1971	37.37	24.08	67013
67015	Dee	Manley Hall	303096	340023	29	1974	2002	30-Oct-2000	440.57	218.11	67015
67019	Tryweryn	Weir X	286121	340437	4	1960	1963	04-Dec-1960	112.7	84.19	67019
67020	Dee	Chester Weir	317403	345370	75	1894	1968	09-Feb-1946	455.76	189.65	67020
68001	Weaver	Ashbrook	365235	350689	66	1937	2002	08-Feb-1946	142.89	46.68	68001
68005	Weaver	Audlem	359817	344402	34	1969	2002	06-Nov-2000	34.48	10.84	68005
68006	Dane	Hulme Walfield	394080	365348	30	1953	1984	08-Sep-1965	113.48	53.48	68006
68007	Wincham Brook	Lostock Gralam	375827	376264	41	1960	2002	03-Feb-1994	30.76	19.72	68007
68011	Arley Brook	Gore Farm	366591	381600	9	1973	1981	18-Nov-1981	11.41	6.11	68011
68020	Gowy	Bridge Trafford	351374	364258	24	1979	2002	06-Nov-2000	20.77	15.16	68020
68044	Dane	Hugbridge	398633	367268	10	1993	2002	23-Oct-1998	177.12	46.63	68044
69017	Goyt	Marple Bridge	402590	382527	33	1969	2002	16-Jul-1973	165.54	48.53	69017
71006	Ribble	Henthorn	380310	457753	35	1968	2002	31-Oct-2000	494	252.38	71006
71008	Hodder	Hodder Place	366843	450185	34	1969	2002	23-Oct-1980	488.14	220.16	71008
71011	Ribble	Arnford	381225	469050	33	1970	2002	01-Feb-1995	149.09	115.77	71011

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
72002	Wyre	St Michaels	354179	445967	41	1962	2002	09-Dec-1983	190.44	148.86	72002
72004	Lune	Caton	366470	482803	35	1968	2002	31-Jan-1995	1181.77	606.74	72004
72005	Lune	Killington New Bridge	362069	503090	32	1969	2002	06-Jan-1999	389.67	225.68	72005
72006	Lune	Kirkby Lonsdale	366219	495009	16	1968	1983	02-Jan-1982	579.46	441.99	72006
72007	Brock	U/S A6	356440	444787	25	1978	2002	22-Aug-1987	63.53	28.01	72007
72011	Rawthey	Brigg Flatts	372441	490983	35	1968	2002	31-Jan-1995	538.65	283.26	72011
72014	Conder	Galgate	351620	459069	36	1966	2002	09-Dec-1983	27.41	15.57	72014
72015	Lune	Lunes Bridge	363046	505307	24	1979	2002	21-Dec-1985	387.36	228.4	72015
72016	Wyre	Scorton Weir	356552	454584	35	1967	2002	22-Nov-1980	150.07	87.36	72016
73002	Crake	Low Nibthwaite	329406	495149	39	1962	2002	04-Jan-1982	32.61	19.29	73002
73003	Kent	Burneside	346201	501646	18	1981	1999	03-Jan-1982	89.01	65.83	73003
73005	Kent	Sedgwick	350609	499239	35	1968	2002	12-Jun-1971	316.07	144.79	73005
73006	Cunsey Beck	Eel House Bridge	335298	497431	30	1970	2002	04-Jan-1982	14.29	7.76	73006
73008	Bela	Beetham	355394	484836	34	1969	2002	06-Jan-1999	80.07	36.57	73008
73009	Sprint	Sprint Mill	349722	503242	34	1969	2002	21-Dec-1985	68.7	37.93	73009
73010	Leven	Newby Bridge FMS	335814	501830	59	1938	2002	02-Dec-1954	135.26	72.56	73010
73011	Mint	Mint Bridge	355566	498624	34	1969	2002	06-Jan-1999	108.37	53.67	73011
73012	Mint	Mint Bridge	350452	500547	29	1974	2002	21-Dec-1985	198.69	124.52	73012
74001	Duddon	Duddon Hall	321459	496418	35	1967	2002	03-Aug-1998	200.67	129.37	74001
74002	Irt	Galesyke	317603	508084	34	1968	2002	06-Dec-1999	41.95	20.66	74002
74003	Ehen	Bleach Green	314176	513743	30	1973	2002	24-Oct-1977	49.88	33.31	74003
74005	Ehen	Braystones	307113	515094	29	1974	2002	31-Oct-1977	110.74	74.32	74005
74006	Calder	Calder Hall	308073	509763	30	1973	2002	03-Aug-1998	108.08	42.05	74006
74007	Esk	Cropple How	319331	501761	29	1974	2002	14-Nov-1980	127.4	102.62	74007
74008	Duddon	Ulpha	323909	499065	30	1973	2002	03-Aug-1998	94.77	68.61	74008
75002	Derwent	Camerton	321058	523737	43	1960	2002	09-Oct-1967	288.15	202.27	75002
75003	Derwent	Ouse Bridge	327778	521979	36	1967	2002	05-Jan-1982	125.22	97.33	75003
75004	Cocker	Southwaite Bridge	316121	520975	37	1966	2002	31-Oct-1977	80.88	46.59	75004
75005	Derwent	Portinscale	330425	519655	31	1972	2002	31-Jan-1995	130.34	98.98	75005
75007	Glenderamackin	Threlkeld	335872	526349	28	1969	2002	18-Oct-1987	83.1	60.72	75007
75009	Greta	Low Briery	333182	522356	32	1971	2002	21-Dec-1985	197.02	103.97	75009
75017	Ellen	Bullgill	319601	538599	27	1976	2002	05-Jan-1999	41.04	33.89	75017
76001	Haweswater Beck	Burnbanks	347035	513023	25	1978	2002	04-Feb-1990	31.44	12.81	76001
76002	Eden	Warwick Bridge	360654	522445	39	1959	1997	23-Mar-1968	860	397.38	76002
76003	Eamont	Udford	346478	519218	42	1961	2002	24-Mar-1968	259.46	174.1	76003
76004	Lowther	Eamont Bridge	350892	515622	41	1962	2002	23-Mar-1968	191.93	95.44	76004
76005	Eden	Temple Sowerby	371161	515038	39	1964	2002	24-Mar-1968	347.92	244.46	76005
76007	Eden	Sheepmount	355830	534240	39	1966	2004	08-Jan-2005	1520	610.75	76007
76008	Irthing	Greenholme	359554	566485	36	1967	2002	06-Jan-1999	264.92	132.15	76008
76010	Petteril	Harraby Green	346101	539276	33	1970	2002	28-Mar-1987	58.46	29.08	76010
76011	Coal Burn	Coalburn	369386	578507	26	1966	2002	30-Aug-1975	6	1.79	76011
76014	Eden	Kirkby Stephen	378419	503113	32	1971	2002	25-Nov-1979	129.62	83.06	76014
76015	Eamont	Pooley Bridge	340740	517213	27	1976	2002	10-Mar-1989	74.16	59.1	76015
76806	Eamont	Pooley Bridge	379229	508221	5	2000	2004	07-Jan-2005	277	164.19	76806
76809	Eamont	Pooley Bridge	336376	538876	8	1997	2004	08-Jan-2005	253	139.6	76809
76810	Eamont	Pooley Bridge	360686	522369	46	1959	2004	08-Jan-2005	935	405.06	76810
76811	Eamont	Pooley Bridge	341782	525858	8	1997	2004	30-Jul-2002	73.4	31.25	76811
77002	Esk	Canonbie	331203	593560	41	1962	2002	09-Oct-1967	570.8	346.01	77002

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
77003	Liddel Water	Rowanburnfoot	350113	591271	29	1974	2002	17-Feb-1997	418.16	296.22	77003
78003	Annan	Brydekirk	310271	593596	36	1967	2002	31-Oct-1977	486.83	314.29	78003
78004	Kinnel Water	Redhall	304389	597392	37	1966	2002	30-Oct-1977	116.94	75.68	78004
78005	Kinnel Water	Bridgemuir	301516	593948	24	1979	2002	21-Sep-1985	151.95	121.37	78005
79002	Nith	Friars Carse	276757	605289	46	1957	2002	16-Jan-1962	908.37	443.69	79002
79003	Nith	Hall Bridge	260365	610481	44	1959	2002	15-Jan-1962	219.76	71.13	79003
79004	Scar Water	Capenoch	276657	598774	40	1963	2002	19-Dec-1982	192.58	132.89	79004
79005	Cluden Water	Fiddlers Ford	279568	586238	40	1963	2002	31-Oct-1977	194.44	105.83	79005
79006	Nith	Drumlanrig	272065	610779	36	1967	2002	30-Oct-1977	530.35	341.65	79006
80001	Urr	Dalbeattie	277424	573857	40	1963	2002	21-Oct-1998	148.8	81.37	80001
81002	Cree	Newton Stewart	237614	579409	40	1963	2002	25-Oct-2000	375.05	227.93	81002
81003	Luce	Airyhemming	216030	569848	37	1966	2002	12-Aug-1987	295.46	163.32	81003
82001	Girvan	Robstone	234068	602995	40	1963	2002	19-Dec-1982	152.74	89.27	82001
82003	Stinchar	Balnowlart	224449	587731	30	1972	2002	19-Dec-1982	279.02	200.68	82003
83003	Ayr	Catrine	265666	627979	33	1970	2002	10-Dec-1994	213.48	103.42	83003
83005	Irvine	Shewalton	249486	638573	27	1971	2002	11-Dec-1994	398.9	212.66	83005
83006	Ayr	Mainholm	256485	622724	28	1975	2002	02-Jan-1981	459.39	248.6	83006
83802	Ayr	Mainholm	252528	636317	88	1913	2002	11-Dec-1994	288.71	74.7	83802
84002	Calder	Muirshiel	228550	664723	21	1951	1972	09-Sep-1962	35.77	16.31	84002
84003	Clyde	Hazelbank	293281	631849	48	1955	2002	12-Dec-1994	567.74	275.63	84003
84004	Clyde	Sills of Clyde	295915	628161	48	1955	2002	16-Jan-1962	411.02	195.3	84004
84005	Clyde	Blairston	286797	637116	47	1955	2002	12-Dec-1994	830.11	375.88	84005
84009	Nethan	Kirkmuirhill	278224	637191	33	1966	2002	30-Oct-1977	80.5	35.56	84009
84011	Gryfe	Craigend	232559	668504	40	1963	2002	03-Dec-1999	142.03	72.58	84011
84014	Avon Water	Fairholm	268831	641740	39	1964	2002	13-Aug-1966	409.73	164.55	84014
84017	Black Cart Water	Milliken Park	234786	659866	35	1968	2002	11-Dec-1994	110.14	34.82	84017
84018	Clyde	Tulliford Mill	293415	628983	35	1968	2002	12-Dec-1994	575.32	247.61	84018
84020	Glazert Water	Milton of Campsie	261408	679737	34	1968	2002	30-Jul-2002	90.88	56.94	84020
85001	Leven	Linnbrane	240563	696549	40	1963	2002	11-Mar-1990	203.58	124.54	85001
85002	Endrick Water	Gaidrew	255288	685415	40	1963	2002	01-Oct-1985	142.37	117.69	85002
85003	Falloch	Glen Falloch	232804	722140	32	1971	2002	22-Dec-1991	217.06	184.25	85003
86001	Little Eachaig	Dalinlongart	211516	681123	36	1967	2002	03-Nov-1979	89.83	43.46	86001
86002	Eachaig	Eckford	212329	694237	19	1968	1990	10-Mar-1990	113.08	80.98	86002
89804	Eachaig	Eckford	218044	733253	26	1977	2002	06-Dec-1999	75.12	58.7	89804
91802	Allt Leachdach	intake	226882	776150	34	1939	1973	25-May-1953	13.3	6.35	91802
93001	Carron	New Kelso	202131	848740	24	1979	2002	02-Jan-1992	313.37	174.34	93001
94001	Ewe	Poolewe	199247	866278	32	1971	2002	07-Feb-1989	220.48	127.76	94001
95001	Inver	Little Assynt	223040	922196	26	1977	2002	07-Feb-1989	59.13	38.7	95001
96001	Halladale	Halladale	289289	947524	28	1975	2002	16-Aug-1990	191.16	106.89	96001
96002	Naver	Apigill	260919	936914	25	1978	2002	04-Oct-1981	236.01	141.76	96002
96003	Strathy	Strathy Bridge	280908	953653	18	1985	2002	09-Nov-2000	104.61	48.41	96003
96004	Strathmore	Allnabad	242592	941764	16	1987	2002	06-Dec-1999	331.01	193.6	96004
97002	Thurso	Halkirk	307125	945990	31	1972	2002	07-Oct-1993	179.22	98.09	97002
201002	Fairywater	Dudgeon Bridge	45100	540100	32	1971	2002	19-Jan-1988	120.83	66.57	201002
201005	Camowen	Camowen Terrace	69300	533200	31	1972	2002	22-Oct-1987	192.91	87.59	201005
201006	Drumragh	Campsie Bridge	54500	526600	31	1972	2002	22-Oct-1987	246.12	106.76	201006
201007	Burn Dennet	Burndennet	61300	565000	28	1975	2002	22-Oct-1987	153.02	76.63	201007
201008	Derg	Castlederg	27500	547900	28	1975	2002	21-Sep-1985	244.92	200.57	201008

No.	River	Gauging station	Easting	Northing	No. of years	Start	End	Date of max	Flow max	QMED	No.
201009	Owenkillew	Crosh	72100	550500	24	1979	2002	21-Oct-1987	508.06	286.3	201009
201010	Mourne	Drumnabuoy House	54700	542000	21	1982	2002	22-Oct-1987	1063.89	593.36	201010
202001	Roe	Ardnargle	86100	573500	28	1975	2002	03-Oct-1981	181.79	146.18	202001
202002	Faughan	Drumahoe	70300	570100	27	1976	2002	21-Oct-1987	253.44	140.71	202002
203010	Blackwater	Maydown Bridge	77000	507400	33	1970	2002	23-Oct-1987	156.99	109.25	203010
203011	Maine	Dromona	125400	573800	31	1969	2002	15-Nov-2002	85.94	59.64	203011
203012	Ballinderry	Ballinderry Bridge	91100	538000	34	1969	2002	22-Oct-1987	208.33	131.82	203012
203018	Six-Mile Water	Antrim	139900	545000	33	1970	2002	21-Oct-1987	163.53	81.84	203018
203019	Claudy	Glenone Bridge	102600	564500	32	1971	2002	23-Oct-1980	59.87	34.35	203019
203020	Moyola	Moyola New Bridge	95400	554600	31	1971	2002	19-Jan-1988	155.69	113.57	203020
203022	Blackwater	Derrymeen Bridge	64600	515200	24	1979	2002	22-Oct-1987	90.1	50.75	203022
203024	Cusher	Gamble's Bridge	108100	494600	32	1971	2002	21-Oct-1987	73.46	47	203024
203026	Glenavy	Glenavy	133400	529000	30	1971	2000	21-Oct-1987	28.72	16.29	203026
203027	Braid	Ballee	133500	564700	31	1972	2002	16-Nov-1995	162.14	90.68	203027
203028	Agivey	Whitehill	97000	574300	31	1972	2002	21-Oct-1987	144.09	62.99	203028
203033	Upper Bann	Bannfield	133300	486500	28	1975	2002	14-Nov-2002	89.08	64.99	203033
203039	Clogh	Tullynewey	130000	571900	22	1981	2002	15-Nov-1995	43.29	37.21	203039
203042	Crumlin	Cidercourt Bridge	133600	533900	24	1979	2002	21-Oct-1987	79.45	37.71	203042
203043	Oonawater	Shanmoy	83400	520300	22	1980	2002	25-Dec-1999	43.47	28.33	203043
203046	Rathmore Burn	Rathmore Bridge	133300	546800	21	1982	2002	24-Dec-1999	15.65	11	203046
203049	Clady	Clady Bridge	138000	536800	21	1982	2002	05-Dec-2001	35.41	22.74	203049
203093	Maine	Shane's Viaduct	128800	564600	20	1983	2002	22-Oct-1987	298.16	211.53	203093
204001	Bush	Seneirl Bridge	120800	590800	31	1972	2002	03-Oct-1981	93.96	62.25	204001
205005	Ravernet	Ravernet	143900	515600	31	1972	2002	26-Nov-1997	32.5	14.49	205005
205008	Lagan	Drumiller	137300	505200	29	1974	2002	28-Dec-1978	45.74	30.43	205008
205011	Annacloy	Kilmore Bridge	148500	509400	24	1979	2002	08-Nov-2000	61.53	35.26	205011
206001	Clanrye	Mountmill Bridge	123400	488200	32	1971	2002	20-Jan-1973	114.37	20.85	206001
206004	Bessbrook	Carnbane	112900	486400	19	1984	2002	24-Oct-1998	11.91	9.29	206004
206006	Bessbrook	Carnbane	142200	481400	48	1895	1942	24-Aug-1942	30.51	15.33	206006
236005	Colebrooke	Ballindarragh Bridge	51300	508200	21	1982	2002	22-Oct-1987	155.28	106.47	236005
236007	Sillees	Drumrainey Bridge	22600	515000	22	1981	2002	21-Dec-1991	37.32	24.14	236007

Appendix B FPEXT, FPLOC and FPDBAR values

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
2001	Helmsdale	Kilphedir	284324	929794	552.57	1117	0.324	0.858	0.0555	1.07	0.67	2001
2002	Brora	Bruachrobie	274462	916259	423.73	1217	0.351	0.845	0.0554	1.023	0.706	2002
3002	Carron	Sgodachail	240482	888010	236.84	1785	0.436	0.974	0.0376	0.864	0.632	3002
3003	Oykel	Easter Turnaig	231271	901365	331.64	1896	0.359	0.915	0.0488	0.92	0.749	3003
4003	Alness	Alness	253141	877497	202.32	1366	0.384	0.908	0.0373	0.999	0.541	4003
4005	Meig	Glenmeannie	220273	850353	123.45	2147	0.389	0.918	0.0366	0.902	0.642	4005
4006	Bran	Dosmucheran	212722	856678	117.54	2203	0.333	0.814	0.0479	0.861	0.717	4006
6003	Moriston	Invermoriston	221387	812362	397.92	2117	0.362	0.985	0.0397	0.892	0.784	6003
6008	Enrick	Mill of Tore	238353	828104	105.98	1292	0.43	0.839	0.0467	0.919	0.608	6008
7001	Findhorn	Shenachie	273215	821452	415.59	1217	0.451	0.982	0.0392	0.763	0.625	7001
7002	Findhorn	Forres	284034	830206	781.74	1065	0.434	0.973	0.0482	0.842	0.703	7002
7003	Lossie	Sheriffmills	314502	853471	216.64	833	0.577	0.979	0.0741	0.684	0.679	7003
7004	Nairn	Firhall	273722	837368	304.96	942	0.587	0.923	0.0682	0.821	0.787	7004
7005	Divie	Dunphail	301689	839889	165.09	870	0.353	0.925	0.0566	0.968	0.542	7005
8001	Spey	Aberlour	292139	810489	2645.6	1133	0.484	0.956	0.0526	0.976	0.873	8001
8002	Spey	Kinrara	270711	793742	1008.94	1316	0.452	0.927	0.0565	0.825	0.966	8002
8004	Avon	Delnashaugh	316609	817588	540.69	1108	0.451	0.989	0.0257	0.905	0.399	8004
8005	Spey	Boat of Garten	275066	796799	1260.92	1277	0.47	0.917	0.0589	0.841	0.973	8005
8006	Spey	Boat o Brig	294879	812741	2852.4	1119	0.485	0.959	0.0525	0.975	0.906	8006
8007	Spey	Invertruim	258191	791354	401.59	1431	0.411	0.945	0.0539	0.803	0.807	8007
8008	Tromie	Tromie Bridge	276489	786784	131.51	1437	0.447	0.898	0.0311	0.792	0.495	8008
8009	Dulnain	Balnaan Bridge	285086	819396	272.2	1012	0.498	0.994	0.0505	0.677	0.576	8009
8010	Spey	Grantown	279940	802927	1745.88	1194	0.484	0.938	0.0612	0.835	0.958	8010
8011	Livet	Minmore	324546	823506	102.89	1001	0.449	1	0.0241	0.737	0.323	8011
9001	Deveron	Avochie	344243	831607	444.8	988	0.505	0.998	0.0342	0.802	0.404	9001
9002	Deveron	Muiresk	348674	840599	961.4	928	0.511	0.997	0.0412	0.878	0.469	9002
9003	Isla	Grange	341980	850067	179.98	900	0.474	0.994	0.0401	0.664	0.416	9003
9004	Bogie	Redcraig	348530	829933	182.4	955	0.567	0.998	0.0313	0.89	0.307	9004
10001	Ythan	Ardlethen	381351	839185	456.97	830	0.614	0.992	0.0432	0.907	0.387	10001
10002	Ugie	Inverugie	396184	850658	325.71	812	0.522	0.984	0.0751	0.797	0.613	10002
10003	Ythan	Ellon	382301	837608	532.29	826	0.62	0.993	0.047	0.878	0.406	10003
11001	Don	Parkhill	357673	817761	1269.46	884	0.584	0.996	0.0588	0.775	0.673	11001
11002	Don	Haughton	348552	814053	792.65	916	0.573	0.997	0.0506	0.753	0.619	11002
11003	Don	Bridge of Alford	339397	812892	509.54	967	0.565	0.996	0.0361	0.813	0.479	11003
11004	Urie	Pitcaple	362209	828797	195.45	870	0.562	0.996	0.0458	0.896	0.411	11004
12001	Dee	Woodend	325598	793481	1380.04	1108	0.506	0.976	0.0468	0.823	0.7	12001
12002	Dee	Park	335381	793266	1833.26	1080	0.507	0.98	0.0483	0.838	0.688	12002
12003	Dee	Polhollick	311368	790126	697.46	1231	0.459	0.986	0.0378	0.863	0.619	12003
12005	Muick	Invermuick	330719	785799	109.39	1244	0.512	0.896	0.0293	0.762	0.403	12005
12006	Gairn	Invergairn	325512	801212	145.91	1048	0.452	0.997	0.0294	0.878	0.395	12006
12007	Dee	Mar Lodge	301326	789773	291.9	1334	0.4	0.989	0.0331	0.833	0.501	12007
12008	Feugh	Heugh Head	360826	787475	232.84	1130	0.427	0.998	0.0381	0.608	0.456	12008
13001	Bervie	Inverbervie	376480	778902	124.47	890	0.554	0.998	0.0594	0.822	0.541	13001

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
14001	Eden	Kemback	330237	711373	308.72	800	0.609	0.992	0.1039	1.002	0.778	14001
15003	Tay	Caputh	268182	753767	3211.11	1609	0.437	0.806	0.0406	0.938	0.847	15003
15006	Tay	Ballathie	283585	754071	4586.97	1424	0.473	0.847	0.0534	0.811	0.915	15006
15007	Tay	Pitnacree	259167	739905	1149.07	1950	0.442	0.836	0.0373	0.912	0.917	15007
15008	Dean Water	Cookston	341011	746580	176.63	840	0.622	0.973	0.1267	0.832	1.007	15008
15010	Isla	Wester Cardean	323994	760470	363.76	1086	0.532	0.94	0.0473	0.71	0.583	15010
15013	Almond	Almondbank	288259	731392	173.32	1394	0.466	0.996	0.0309	0.732	0.474	15013
15016	Tay	Kenmore	253572	733602	598.42	2129	0.423	0.76	0.0344	1.099	0.796	15016
16001	Earn	Kinkell Bridge	275774	722833	584.7	1505	0.487	0.894	0.0561	0.723	0.729	16001
16003	Ruchill Water	Cultybraggan	269860	716406	98.48	1900	0.428	1	0.0333	0.769	0.486	16003
16004	Earn	Forteviot Bridge	280547	720580	783.72	1404	0.51	0.916	0.061	0.776	0.825	16004
17001	Carron	Headswood	273125	684424	117.12	1530	0.372	0.844	0.0397	0.769	0.489	17001
19004	North Esk	Dalmore Weir	319829	657686	79.86	949	0.561	0.975	0.0316	0.95	0.285	19004
19008	South Esk	Prestonholm	331180	655398	113.44	859	0.592	0.888	0.0418	1.011	0.363	19008
19011	North Esk	Dalkeith Palace	321728	659964	133.52	906	0.551	0.965	0.0329	0.879	0.327	19011
20001	Tyne	East Linton	347341	666383	307.14	713	0.489	0.986	0.0503	0.87	0.404	20001
20002	West Peffer Burn	Luffness	352595	680164	26.31	616	0.471	0.996	0.1279	0.832	0.851	20002
20003	Tyne	Spilmersford	342842	663792	162.76	724	0.52	0.987	0.0452	0.826	0.337	20003
20005	Birns Water	Saltoun Hall	345090	662102	92.61	762	0.536	0.989	0.0297	0.895	0.247	20005
20007	Gifford Water	Lennoxlove	353773	665941	67.75	770	0.527	0.977	0.0293	0.681	0.245	20007
21001	Fruid Water	Fruid	310750	616956	22.17	1699	0.392	1	0.0113	0.931	0.144	21001
21003	Tweed	Peebles	314086	636304	698.01	1140	0.517	0.974	0.0505	0.854	0.615	21003
21005	Tweed	Lyne Ford	310348	629329	377.16	1255	0.507	0.965	0.0481	0.789	0.622	21005
21007	Ettrick Water	Lindean	330137	621040	502.73	1306	0.443	0.928	0.0386	0.767	0.651	21007
21008	Teviot	Ormiston Mill	356832	614437	1121.49	937	0.458	0.987	0.0464	0.801	0.611	21008
21009	Tweed	Norham	352257	629303	4398.66	955	0.495	0.981	0.0544	0.846	0.702	21009
21011	Yarrow Water	Philiphaugh	327398	624661	232.41	1347	0.443	0.919	0.0267	0.727	0.454	21011
21012	Teviot	Hawick	343049	607412	324.39	1149	0.429	0.993	0.0323	0.801	0.448	21012
21013	Gala Water	Galashiels	341475	648495	205.45	930	0.531	0.999	0.0348	0.871	0.44	21013
21015	Leader Water	Earlston	353943	650943	239.07	853	0.563	0.999	0.0338	0.793	0.416	21015
21016	Eye Water	Eyemouth Mill	385382	663511	118.86	730	0.597	0.997	0.0356	0.854	0.313	21016
21017	Ettrick Water	Brockhoperig	320191	610867	38.59	1740	0.421	1	0.012	0.721	0.213	21017
21019	Manor Water	Cademuir	320823	631648	59.98	1344	0.482	0.997	0.0313	0.565	0.436	21019
21020	Yarrow Water	Gordon Arms	322923	622849	153.94	1496	0.395	0.883	0.0187	0.651	0.307	21020
21021	Tweed	Sprouston	340986	628413	3345.74	1014	0.496	0.978	0.046	0.9	0.651	21021
21022	Whiteadder Water	Hutton Castle	371489	657271	502.24	814	0.518	0.981	0.047	0.75	0.459	21022
21024	Jed Water	Jedburgh	365676	610828	139.27	915	0.436	0.997	0.0284	0.881	0.383	21024
21025	Ale Water	Ancrum	347712	621531	173.94	926	0.391	0.948	0.0606	0.852	0.682	21025
21027	Blackadder Water	Mouth Bridge	371059	650492	155.39	774	0.518	0.997	0.07	0.962	0.573	21027
21029	Tweed	Glenbreck	305784	617310	34.37	1532	0.353	1	0.0212	0.794	0.316	21029
21030	Megget Water	Henderland	318923	622287	55.97	1670	0.393	1	0.0085	0.702	0.211	21030
21031	Till	Etal	394992	625894	634.78	827	0.504	0.992	0.0672	0.757	0.658	21031
21032	Glen	Kirknewton	385595	625684	196.12	877	0.456	0.986	0.0395	0.793	0.436	21032
21034	Yarrow Water	Craig Douglas	321501	621791	116.03	1555	0.39	0.847	0.016	0.694	0.268	21034
22001	Coquet	Morwick	400758	603911	578.21	850	0.393	0.993	0.0403	0.787	0.496	22001
22002	Coquet	Bygate	383302	611166	60.07	1020	0.413	1	0.0077	0.755	0.11	22002
22003	Usway Burn	Shillmoor	388728	614173	21.87	1056	0.302	1	0.0061	0.937	0.083	22003
22004	Aln	Hawkhill	410419	614239	202.93	758	0.427	0.997	0.0406	0.864	0.366	22004

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
22006	Blyth	Hartford Bridge	411285	575860	273.62	696	0.333	0.99	0.1148	0.936	0.838	22006
22007	Wansbeck	Mitford	404914	587654	282.03	794	0.347	0.973	0.0591	0.919	0.547	22007
22009	Coquet	Rothbury	392511	606428	345.99	905	0.395	0.994	0.0359	0.62	0.464	22009
23001	Tyne	Bywell	378954	572789	2172.36	1016	0.318	0.961	0.0504	0.839	0.719	23001
23002	Derwent	Eddys Bridge	396338	549462	118.07	943	0.316	0.996	0.0203	0.863	0.234	23002
23003	North Tyne	Reaverhill	377080	589424	1012.97	1023	0.31	0.993	0.0471	0.764	0.666	23003
23004	South Tyne	Haydon Bridge	373642	554530	749.9	1147	0.298	0.989	0.044	0.817	0.608	23004
23005	North Tyne	Tarset	365543	590723	283.38	1230	0.274	1	0.025	0.836	0.349	23005
23006	South Tyne	Featherstone	369209	547794	322.97	1331	0.27	0.995	0.0303	0.77	0.459	23006
23007	Derwent	Rowlands Gill	402780	551182	243.84	849	0.335	0.908	0.0264	0.842	0.33	23007
23008	Rede	Rede Bridge	384095	596079	345.2	941	0.322	0.978	0.0409	0.818	0.529	23008
23009	South Tyne	Alston	371823	540057	118.62	1522	0.266	0.999	0.0251	0.742	0.379	23009
23010	Tarset Burn	Greenhaugh	376212	592868	95.57	993	0.305	1	0.0292	0.848	0.35	23010
23011	Kielder Burn	Kielder	366671	598858	58.81	1199	0.273	1	0.0201	0.676	0.285	23011
23012	East Allen	Wide Eals	383546	551702	88.18	1050	0.298	0.997	0.0268	0.848	0.371	23012
23013	West Allen	Hindley Wrae	377486	551713	78.54	1156	0.28	0.998	0.0224	0.752	0.292	23013
23015	North Tyne	Barrasford	377644	588998	1049.61	1013	0.311	0.989	0.0489	0.762	0.675	23015
24001	Wear	Sunderland Bridge	404825	534972	661.04	933	0.342	0.978	0.0346	0.726	0.486	24001
24003	Wear	Stanhope	388676	539354	173.41	1279	0.3	0.978	0.0195	0.739	0.346	24003
24004	Bedburn Beck	Bedburn	405023	530533	74.13	895	0.362	0.999	0.0106	0.727	0.139	24004
24006	Rookhope Burn	Eastgate	391865	542746	36.62	1126	0.293	0.994	0.0177	0.936	0.496	24006
24007	Browney	Lanchester	411164	544143	44.59	797	0.333	1	0.0147	0.734	0.156	24007
24008	Wear	Witton Park	398825	536850	455.1	1034	0.338	0.97	0.024	0.771	0.386	24008
25001	Tees	Broken Scar	396415	521254	847.7	1122	0.354	0.945	0.0526	0.742	0.719	25001
25003	Trout Beck	Moor House	373799	531877	11.46	1904	0.227	1	0.0412	0.709	0.661	25003
25005	Leven	Leven Bridge	453156	507565	194.15	726	0.381	0.994	0.1067	0.933	0.835	25005
25006	Greta	Rutherford Bridge	393998	510668	86.81	1127	0.241	0.999	0.0421	0.96	0.515	25006
25008	Tees	Barnard Castle	388625	525152	510.17	1310	0.321	0.912	0.0345	0.944	0.53	25008
25009	Tees	Low Moor	406923	520355	1267.1	966	0.374	0.958	0.0784	0.785	0.909	25009
25011	Langdon Beck	Langdon	385506	533451	12.79	1463	0.237	1	0.0125	0.74	0.175	25011
25012	Harwood Beck	Harwood	381653	533545	24.58	1577	0.261	1	0.0212	0.743	0.302	25012
25018	Tees	Middleton in Teesdale	383018	529931	242.36	1532	0.283	0.939	0.0336	0.974	0.539	25018
25019	Leven	Easby	460962	509663	15.07	830	0.525	1	0.0194	0.769	0.183	25019
26003	Foston Beck	Foston Mill	504662	465194	59.4	698	0.88	0.987	0.1057	0.409	0.841	26003
26802	Foston Beck	Foston Mill	488328	466463	15.85	757	0.959	1	0.0305	0.853	0.228	26802
26803	Foston Beck	Foston Mill	498435	463033	32.43	721	0.949	1	0.0159	0.59	0.116	26803
27002	Wharfe	Flint Mill Weir	408602	459310	759.03	1163	0.386	0.927	0.0532	0.772	0.807	27002
27007	Ure	Westwick Lock	408676	481762	912.58	1120	0.42	0.981	0.0674	0.694	1.075	27007
27008	Swale	Leckby Grange	422266	495156	1350.24	835	0.436	0.994	0.1182	0.699	1.105	27008
27009	Ouse	Skelton	422906	481304	3300.8	899	0.439	0.983	0.1357	0.663	1.402	27009
27010	Hodge Beck	Bransdale Weir	461816	498131	18.84	987	0.341	1	0.0094	1.047	0.131	27010
27014	Rye	Little Habton	463598	488603	680.84	824	0.547	0.996	0.0923	0.462	0.867	27014
27024	Swale	Richmond	397707	501071	377.97	1226	0.342	0.999	0.028	0.854	0.589	27024
27027	Wharfe	Ilkley	398527	466714	445.22	1369	0.366	0.976	0.0362	0.89	0.523	27027
27034	Ure	Kilgram Bridge	396729	487690	510.9	1338	0.386	0.99	0.0452	0.856	0.955	27034
27035	Aire	Kildwick Bridge	393465	455405	283.47	1151	0.385	0.977	0.0734	0.791	0.844	27035
27038	Costa Beck	Gatehouses	478405	486210	7.98	722	0.774	0.99	0.1253	0.383	0.486	27038
27041	Derwent	Buttercrambe	476234	483445	1594.22	765	0.608	0.994	0.141	0.819	1.098	27041

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
27043	Wharfe	Addingham	398150	467369	429.98	1385	0.366	0.975	0.035	0.909	0.501	27043
27051	Crimple	Burn Bridge	426492	452134	8.15	855	0.309	1	0.0133	0.711	0.144	27051
27053	Nidd	Birstwith	411968	468699	219.28	1218	0.357	0.913	0.0291	0.728	0.472	27053
27056	Pickering Beck	Ings Bridge	482273	491124	67.62	834	0.691	1	0.0381	0.66	0.363	27056
27059	Laver	Ripon	421740	473034	78.28	912	0.42	0.982	0.0451	0.766	0.459	27059
27084	Eastburn Beck	Crosshills	397155	443837	41.01	1129	0.315	0.998	0.025	0.55	0.287	27084
27086	Skell	Alma Weir	422502	471702	117.35	899	0.422	0.97	0.0458	0.759	0.457	27086
27087	Derwent	Low Marishes	493360	484721	475.92	741	0.684	0.996	0.1874	0.65	1.313	27087
27089	Wharfe	Tadcaster	410930	458204	815.36	1130	0.416	0.93	0.0576	0.753	0.857	27089
27090	Swale	Catterick Bridge	401958	501699	497.61	1123	0.381	0.998	0.0383	0.746	0.668	27090
27201	Swale	Catterick Bridge	395621	427036	172.96	1357	0.355	0.94	0.0233	0.977	0.372	27201
28008	Dove	Rocester Weir	412867	354822	397.97	1022	0.555	0.991	0.0405	0.787	0.488	28008
28011	Derwent	Matlock Bath	418165	376336	687.29	1114	0.565	0.947	0.0303	0.785	0.373	28011
28018	Dove	Marston on Dove	408533	349064	883.12	936	0.528	0.976	0.0746	0.679	0.89	28018
28023	Wye	Ashford	411226	374534	152.4	1165	0.678	0.976	0.0232	1.019	0.208	28023
28024	Wreake	Syston Mill	476502	316705	417.01	634	0.403	0.953	0.0885	0.905	0.786	28024
28031	Manifold	Ilam	407654	356758	148.45	1098	0.455	1	0.0327	0.912	0.424	28031
28033	Dove	Hollinsclough	404552	368129	7.93	1346	0.403	1	0.0075	0.802	0.086	28033
28041	Hamps	Waterhouses	405257	353971	36.97	1085	0.301	1	0.0326	0.663	0.39	28041
28043	Derwent	Chatsworth	418886	383582	344.36	1170	0.461	0.909	0.0258	0.73	0.341	28043
28046	Dove	Izaak Walton	411773	361404	85.7	1098	0.651	1	0.0265	0.944	0.287	28046
28055	Ecclesbourne	Duffield	428768	349415	50.97	852	0.455	0.997	0.0262	0.631	0.272	28055
28058	Henmore Brook	Ashbourne	422849	349884	38.48	895	0.448	0.977	0.0302	0.593	0.315	28058
28061	Churnet	Basford Bridge	396765	356765	136.34	976	0.442	0.927	0.0527	0.788	0.581	28061
28070	Burbage Brook	Burbage	426299	382091	8.45	1006	0.426	1	0.031	1.242	0.217	28070
29001	Waithe Beck	Brigsley	520771	395873	108.14	691	0.883	0.961	0.0415	0.816	0.281	29001
29002	Great Eau	Claythorpe Mill	536273	377820	80.4	692	0.713	0.952	0.0626	0.64	0.401	29002
29003	Lud	Louth	529502	384953	55.72	698	0.82	0.958	0.0247	0.852	0.184	29003
29004	Ancholme	Bishopbridge	501036	386992	59.03	615	0.558	0.996	0.2478	0.772	1.285	29004
29009	Ancholme	Toft Newton	499618	385709	29.52	616	0.625	0.997	0.2063	0.731	0.959	29009
30003	Bain	Fulsby Lock	526134	376051	199.42	667	0.757	0.963	0.0808	0.782	0.621	30003
30004	Lymn	Partney Mill	534402	371019	60.24	686	0.568	0.979	0.0606	0.952	0.465	30004
30005	Witham	Saltersford total	490684	325074	123.5	646	0.761	0.973	0.0925	1.203	0.485	30005
30011	Bain	Goulceby Bridge	523650	386241	64.11	695	0.843	0.949	0.0521	1.022	0.308	30011
30014	Pointon Lode	Pointon	508244	329902	10.94	591	0.338	1	0.1046	0.635	0.738	30014
30017	Witham	Colsterworth	491229	320258	50.13	641	0.656	0.993	0.1238	1.166	0.675	30017
31004	Welland	Tallington	483677	298564	708	632	0.476	0.925	0.0867	0.967	0.751	31004
31005	Welland	Tixover	477726	293382	419.59	636	0.377	0.971	0.098	0.901	0.831	31005
31010	Chater	Fosters Bridge	487563	303210	68.85	639	0.529	0.998	0.0318	0.808	0.293	31010
31023	West Glen	Easton Wood	495229	325297	4.32	641	0.32	1	0.0516	0.966	0.3	31023
31025	Gwash South Arm	Manton	482615	306835	23.93	663	0.306	0.995	0.0266	0.619	0.257	31025
32003	Harpers Brook	Old Mill Bridge	491255	284601	70.46	622	0.415	1	0.0618	1.013	0.466	32003
33005	Bedford Ouse	Thornborough Mill	467160	231972	387.74	655	0.48	0.983	0.1108	0.921	0.771	33005
33007	Nar	Marham	582917	315878	147.47	683	0.803	0.926	0.1336	0.974	0.716	33007
33011	Little Ouse	County Bridge Euston	599445	278215	130.1	596	0.653	0.985	0.1461	0.982	0.815	33011
33012	Kym	Meagre Farm	506371	265471	137.99	585	0.309	0.992	0.1207	0.877	0.767	33012
33013	Sapiston	Rectory Bridge	594868	268499	196.18	589	0.611	0.975	0.1367	1.03	0.78	33013
33018	Tove	Cappenham Bridge	463136	247958	132.65	661	0.368	0.986	0.0627	0.798	0.562	33018

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
33019	Thet	Melford Bridge	599012	291010	311.37	620	0.707	0.932	0.1901	1.039	1.024	33019
33020	Alconbury Brook	Brampton	512089	276527	212.63	564	0.319	0.999	0.1742	0.807	1.065	33020
33021	Rhee	Burnt Mill	534753	244427	306.06	559	0.715	0.994	0.1778	0.884	0.933	33021
33027	Rhee	Wimpole	528835	243642	128.42	558	0.613	1	0.1962	0.826	0.998	33027
33029	Stringside	Whitebridge	573505	305835	95.53	628	0.864	0.991	0.2263	0.782	0.951	33029
33032	Heacham	Heacham	574858	333466	56.18	688	0.968	0.983	0.1161	1.199	0.533	33032
33034	Little Ouse	Abbey Heath	596477	281368	707.72	607	0.694	0.959	0.1632	1.033	0.899	33034
33037	Bedford Ouse	Newport Pagnell	470035	238160	801.65	648	0.437	0.943	0.1041	0.928	0.878	33037
33044	Thet	Bridgham	600029	291906	274.99	620	0.681	0.942	0.1991	1	1.041	33044
33045	Wittle	Quidenham	605154	287146	27.55	608	0.534	0.974	0.1771	1.079	0.859	33045
33046	Thet	Red Bridge	602298	295014	143.43	624	0.581	0.944	0.2033	0.995	1.03	33046
33049	Stanford Water	Buckenham Tofts	590032	295982	46.42	645	0.853	0.915	0.1649	1.063	0.791	33049
33051	Cam	Chesterford	551708	236036	140.09	599	0.576	0.993	0.0518	0.973	0.406	33051
33054	Babingley	Castle Rising	574758	325733	48.51	686	0.906	0.944	0.1181	0.759	0.598	33054
33055	Granta	Babraham	557649	246183	101.8	579	0.637	0.999	0.0614	0.792	0.405	33055
33057	Ouzel	Leighton Buzzard	493921	221073	122.39	643	0.524	0.991	0.1574	0.847	0.885	33057
33063	Little Ouse	Knettishall	601051	277607	103.32	595	0.596	0.982	0.1498	0.938	0.834	33063
34001	Yare	Colney	606922	304371	228.81	635	0.528	0.971	0.1386	1.028	0.849	34001
34003	Bure	Ingworth	613109	333025	161.41	669	0.778	0.974	0.0851	0.967	0.495	34003
34004	Wensum	Costessey Mill	597805	322666	559.72	672	0.689	0.93	0.1299	0.989	0.852	34004
34005	Tud	Costessey Park	605697	311919	72.12	649	0.598	0.973	0.1578	1.094	0.867	34005
34012	Burn	Burnham Overy	584689	337532	83.87	668	0.965	0.997	0.0983	1.106	0.451	34012
35008	Gipping	Stowmarket	601946	259639	126.98	577	0.402	0.996	0.0988	1.062	0.567	35008
36002	Glem	Glemsford	578966	252844	85.63	598	0.402	0.982	0.056	0.981	0.433	36002
36003	Box	Polstead	593948	242065	56.46	566	0.554	0.993	0.0936	1.057	0.504	36003
36004	Chad Brook	Long Melford	586647	250956	50.32	589	0.44	1	0.065	0.997	0.457	36004
36005	Brett	Hadleigh	596377	249596	155.85	580	0.428	0.994	0.0764	1.1	0.494	36005
36006	Stour	Langham	579555	245068	571.36	580	0.509	0.985	0.0861	0.848	0.768	36006
36007	Belchamp Brook	Bardfield Bridge	581018	240358	58.16	560	0.523	0.996	0.0789	0.992	0.491	36007
36008	Stour	Westmill	569913	247315	222.82	589	0.413	0.994	0.0684	0.912	0.582	36008
36009	Brett	Cockfield	590503	255182	25.62	598	0.395	1	0.1129	1.145	0.618	36009
36010	Bumpstead Brook	Broad Green	565863	241222	27.58	588	0.387	0.999	0.0447	0.905	0.352	36010
36012	Stour	Kedington	567272	251505	76.64	599	0.396	0.99	0.06	0.984	0.475	36012
36015	Stour	Lamarsh	576876	247076	481.29	583	0.474	0.987	0.0777	0.871	0.655	36015
37003	Ter	Crabbs Bridge	573430	217809	77.76	570	0.461	0.994	0.1153	1.142	0.607	37003
37005	Colne	Lexden	581429	232555	235.9	566	0.537	0.97	0.0761	0.952	0.549	37005
37010	Blackwater	Appleford Bridge	575177	227559	247.09	572	0.477	0.992	0.0981	0.816	0.658	37010
37011	Chelmer	Churchend	560093	228787	72.78	591	0.448	0.992	0.0595	0.99	0.46	37011
37012	Colne	Poolstreet	572778	237726	64.54	574	0.403	0.992	0.0674	1.034	0.449	37012
37013	Sandon Brook	Sandon Bridge	575428	201211	74.95	575	0.276	0.855	0.092	1.012	1.573	37013
37014	Roding	High Ongar	558197	213815	92.74	598	0.403	0.986	0.107	1.012	0.779	37014
37016	Pant	Copford Hall	562345	235668	63.78	588	0.404	0.997	0.0691	1.082	0.488	37016
37017	Blackwater	Stisted	567758	232355	140.38	579	0.493	0.994	0.0688	1.001	0.535	37017
37020	Chelmer	Felsted	562293	226088	132.96	588	0.468	0.982	0.0659	0.965	0.49	37020
38002	Ash	Mardock	543206	222683	78.1	619	0.505	1	0.0491	0.938	0.424	38002
38004	Rib	Wadesmill	537728	228623	136.69	625	0.469	0.999	0.0538	0.948	0.492	38004
38026	Pincey Brook	Sheering Hall	554007	216705	52.85	599	0.388	0.984	0.0892	1.018	0.61	38026
39002	Thames	Days Weir	430925	212889	3480.01	690	0.65	0.953	0.1758	0.879	1.632	39002

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
39006	Windrush	Newbridge	418884	219840	361.6	744	0.79	0.951	0.075	0.589	0.647	39006
39008	Thames	Eynsham	414913	204780	1626.71	730	0.686	0.946	0.1923	0.827	1.933	39008
39016	Kennet	Theale	433673	170432	1037.36	758	0.766	0.965	0.0782	0.811	0.649	39016
39018	Kennet	Theale	437749	192940	248.21	637	0.635	0.986	0.2001	0.862	1.157	39018
39019	Lambourn	Shaw	437599	178291	235.21	736	0.839	0.979	0.034	0.88	0.231	39019
39020	Coln	Bibury	405568	216076	107.29	821	0.858	0.968	0.0291	0.8	0.259	39020
39025	Enborne	Brimpton	448699	160992	142.08	789	0.5	0.978	0.0755	0.79	0.731	39025
39026	Cherwell	Banbury	449514	249775	204.57	664	0.41	0.95	0.1055	0.866	0.835	39026
39028	Dun	Hungerford	425985	164944	100.1	786	0.768	0.988	0.0498	1.008	0.274	39028
39029	Tillingbourne	Shalford	508055	146327	58.78	810	0.885	0.879	0.0289	0.664	0.291	39029
39034	Evenlode	Cassington Mill	432691	223000	427.14	691	0.699	0.965	0.0682	0.996	0.541	39034
39035	Churn	Cerney Wick	400043	209009	126.74	833	0.825	0.89	0.0623	0.482	0.516	39035
39036	Law Brook	Albury	507366	144917	16.05	819	0.888	0.96	0.0173	0.588	0.163	39036
39037	Kennet	Marlborough	410751	170291	136.48	772	0.959	1	0.0763	1.091	0.459	39037
39042	Leach	Priory Mill Lechlade	415948	209471	77.57	736	0.865	0.971	0.0822	0.612	0.552	39042
39081	Ock	Abingdon	437189	192523	233.6	639	0.623	0.986	0.2022	0.851	1.162	39081
40004	Rother	Udiam	566051	125058	204.71	857	0.388	0.975	0.0575	0.674	0.715	40004
40005	Beult	Stile Bridge	585642	142131	278.05	691	0.353	0.992	0.184	0.886	1.227	40005
40009	Teise	Stone Bridge	566350	135405	134.5	812	0.443	0.904	0.0413	0.755	0.487	40009
41003	Cuckmere	Sherman Bridge	556551	114104	130.45	814	0.405	0.978	0.0966	0.759	0.956	41003
41005	Ouse	Gold Bridge	535445	127422	182.48	835	0.494	0.922	0.0445	0.771	0.468	41005
41011	Rother	Iping Mill	477884	125009	156.9	921	0.675	0.973	0.078	0.858	0.691	41011
41014	Arun	Pallingham Quay	507351	132316	382.69	805	0.39	0.958	0.0849	0.824	0.864	41014
41015	Ems	Westbourne	478470	113230	57.92	899	0.904	0.976	0.0387	0.657	0.291	41015
41016	Cuckmere	Cowbeech	560883	118771	19.09	855	0.471	0.966	0.0434	0.516	0.476	41016
41018	Kird	Tanyards	498540	128368	67.25	820	0.36	0.961	0.1069	0.866	0.985	41018
41020	Bevern Stream	Clappers Bridge	536753	115688	35.42	886	0.355	0.993	0.0757	0.953	0.688	41020
41022	Lod	Halfway Bridge	491432	126898	52.44	857	0.48	0.951	0.0611	0.876	0.649	41022
41023	Lavant	Graylingwell	487719	113373	86.29	922	0.935	1	0.034	0.656	0.235	41023
41025	Loxwood Stream	Drungewick	498040	134412	92.96	812	0.321	0.962	0.0936	0.712	1.023	41025
41028	Chess Stream	Chess Bridge	525651	115288	24.92	849	0.497	0.983	0.0971	0.722	0.779	41028
42003	Lymington	Brockenhurst	426184	105415	99.67	854	0.386	0.997	0.1071	0.709	0.845	42003
42005	Wallop Brook	Broughton	428891	137030	53.51	770	0.955	1	0.0537	0.951	0.266	42005
42006	Meon	Mislingford	463826	120638	75.85	896	0.952	0.979	0.0488	0.907	0.359	42006
42008	Cheriton Stream	Sewards Bridge	461728	127314	74.34	885	0.941	0.995	0.0403	0.824	0.259	42008
42009	Candover Stream	Borough Bridge	460963	141287	72.07	819	0.951	0.93	0.0393	0.926	0.253	42009
42010	Itchen	Highbridge+Allbrook	457279	132838	327.81	834	0.949	0.949	0.0513	0.8	0.373	42010
42011	Hamble	Frogmill	456316	119165	55.33	838	0.746	0.991	0.0443	0.736	0.337	42011
42014	Blackwater	Ower	426272	120791	102.42	837	0.479	0.979	0.0532	0.855	0.423	42014
43003	Avon	East Mills	405962	140935	1459.55	807	0.894	0.985	0.0694	0.868	0.622	43003
43004	Bourne	Laverstock	421744	146232	165.21	768	0.952	1	0.0561	0.918	0.358	43004
43005	Avon	Amesbury	413152	155342	326.55	744	0.903	1	0.071	1.054	0.43	43005
43006	Nadder	Wilton	395753	129698	215.68	875	0.763	0.976	0.0472	0.821	0.423	43006
43007	Stour	Throop	385102	113186	1064.02	861	0.664	0.988	0.1124	0.921	1.024	43007
43008	Wylye	South Newton	396257	142669	447.94	830	0.937	0.976	0.0518	0.887	0.366	43008
43009	Stour	Hammoon	376203	119594	518.88	849	0.442	0.992	0.1227	0.851	0.953	43009
43010	Allen	Loverley Mill	398756	115822	94.89	872	0.944	0.985	0.0523	0.645	0.368	43010
43012	Wylye	Norton Bavant	385023	140062	114.01	925	0.885	0.975	0.0592	0.788	0.365	43012

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
43014	East Avon	Upavon	416333	160687	85.83	759	0.838	1	0.1188	0.934	0.626	43014
43017	West Avon	Upavon	406844	160525	84.62	744	0.872	1	0.1187	0.935	0.625	43017
43018	Allen	Walford Mill	398328	111954	170.88	860	0.914	0.979	0.0675	0.712	0.452	43018
43019	Shreen Water	Colesbrook	380592	131883	30.36	884	0.565	0.993	0.063	0.779	0.433	43019
43801	Shreen Water	Colesbrook	396070	147184	68	807	0.974	1	0.0246	0.701	0.193	43801
43806	Shreen Water	Colesbrook	382845	136388	50.04	968	0.931	1	0.0367	0.982	0.233	43806
44001	Frome	East Stoke Total	367872	93022	414.4	968	0.778	0.968	0.0711	0.651	0.554	44001
44002	Piddle	Baggs Mill	377762	97463	183.79	942	0.86	0.969	0.0537	0.663	0.437	44002
44003	Asker	Bridport	351377	95390	48.51	924	0.696	0.994	0.0249	0.583	0.275	44003
44004	Frome	Dorchester Total	361401	98017	205.67	1010	0.775	0.971	0.0348	0.66	0.305	44004
44006	Sydling Water	Sydling St Nicholas	362829	101665	12.06	1030	0.879	0.944	0.0162	0.564	0.11	44006
44008	Sth Winterbourne	W'bourne Steepleton	359404	90873	20.17	1012	0.811	1	0.0149	0.668	0.11	44008
44801	Sth Winterbourne	W'bourne Steepleton	352000	101792	11.76	1030	0.597	0.923	0.0183	0.595	0.153	44801
44807	Sth Winterbourne	W'bourne Steepleton	379332	82697	16.78	894	0.786	1	0.015	0.636	0.124	44807
44810	Sth Winterbourne	W'bourne Steepleton	373980	98698	107.23	969	0.882	0.99	0.0357	0.649	0.307	44810
45001	Exe	Thorverton	291198	125205	608.13	1249	0.526	0.985	0.0313	0.7	0.451	45001
45002	Exe	Stoodleigh	289667	130913	420.71	1361	0.495	0.979	0.0216	0.799	0.324	45002
45003	Culm	Wood Mill	308880	111882	228.88	971	0.585	0.993	0.065	0.63	0.574	45003
45004	Axe	Whitford	332345	104570	288.53	994	0.498	0.996	0.0383	0.742	0.408	45004
45005	Otter	Dotton	313401	101018	202.79	971	0.549	0.996	0.0502	0.746	0.504	45005
45008	Otter	Fenny Bridges	317423	105040	105.29	1040	0.491	0.994	0.0361	0.701	0.363	45008
45009	Exe	Pixton	291729	134753	147.85	1375	0.548	0.95	0.017	0.818	0.238	45009
45012	Creedy	Cowley	281643	100832	263.63	909	0.577	0.993	0.0401	0.634	0.421	45012
45013	Tale	Fairmile	308981	102297	31.4	922	0.514	0.998	0.048	0.771	0.431	45013
45816	Tale	Fairmile	300160	130640	6.81	1210	0.59	1	0.0114	0.734	0.117	45816
45817	Tale	Fairmile	299063	130043	1.74	1207	0.603	1	0.0172	0.718	0.141	45817
45818	Tale	Fairmile	299130	134000	9.85	1270	0.578	1	0.0056	0.61	0.064	45818
45819	Tale	Fairmile	262294	139416	78.06	1342	0.575	0.973	0.0113	0.782	0.144	45819
46003	Dart	Austins Bridge	267325	74040	249.75	1771	0.523	0.995	0.0359	1.053	0.519	46003
46005	East Dart	Bellever	263051	81181	22.27	2095	0.363	1	0.042	0.863	0.588	46005
46007	West Dart	Dunnabridge	260714	76572	47.49	1987	0.367	1	0.0489	0.846	0.637	46007
46008	Avon	Loddiswell	270511	57787	102.37	1549	0.554	0.986	0.0299	0.941	0.512	46008
47001	Tamar	Gunnislake	234596	90512	920.16	1215	0.481	0.993	0.044	0.96	0.597	47001
47004	Lynher	Pillaton Mill	229409	72589	135.29	1423	0.549	0.996	0.0339	0.987	0.457	47004
47005	Ottery	Werrington Park	223677	91033	121.64	1199	0.45	0.999	0.0465	0.796	0.557	47005
47006	Lyd	Lifton Park	246584	88524	220.39	1228	0.485	0.996	0.035	0.785	0.449	47006
47007	Yealm	Puslinch	260299	57994	56.9	1428	0.549	0.987	0.0321	0.728	0.406	47007
47008	Thrushel	Tinhay	245181	91620	112.7	1144	0.422	0.999	0.0362	0.803	0.447	47008
47009	Tiddy	Tideford	231066	64366	37.37	1276	0.591	1	0.0237	0.695	0.309	47009
47010	Tamar	Crowford Bridge	228557	108393	77.73	1181	0.386	0.947	0.0635	0.763	0.697	47010
47011	Plym	Carn Wood	256358	66809	79.4	1618	0.481	0.95	0.0281	0.873	0.387	47011
47013	Withey Brook	Bastreet	223310	75487	16.03	1684	0.367	0.998	0.0593	0.71	0.636	47013
47014	Walkham	Horrabridge	254962	73828	44.31	1664	0.585	1	0.0228	0.876	0.321	47014
47015	Tavy	Denham / Ludbrook	251815	76692	198.07	1555	0.553	0.999	0.0295	0.98	0.548	47015
47018	Thrushel	Hayne Bridge	247809	91097	57.5	1164	0.419	0.999	0.0433	0.838	0.519	47018
47020	Inny	Beals Mill	224015	81813	102.05	1429	0.576	1	0.0358	0.937	0.476	47020
47804	Inny	Beals Mill	242967	95441	7.17	1150	0.398	1	0.0059	1.033	0.044	47804
47805	Inny	Beals Mill	245919	95770	11.34	1188	0.411	1	0.0066	0.609	0.092	47805

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
48001	Fowey	Trekeivesteps	220765	74772	36.8	1636	0.445	0.938	0.0435	0.849	0.571	48001
48003	Fal	Tregony	194928	54536	89.03	1211	0.546	0.983	0.0656	1.109	0.624	48003
48004	Warleggan	Trengoffe	215277	71462	25.26	1445	0.499	0.978	0.035	1.14	0.417	48004
48006	Cober	Helston	167298	32352	40.83	1206	0.671	0.979	0.0337	0.879	0.291	48006
48007	Kennal	Ponsanooth	172159	36762	26.83	1294	0.736	0.866	0.0258	0.946	0.196	48007
48009	St Neot	Craigshill Wood	218187	71271	22.91	1512	0.463	0.982	0.0224	0.98	0.253	48009
48010	Seaton	Trebrownbridge	227802	64417	38.57	1325	0.59	0.993	0.0202	0.932	0.24	48010
48011	Fowey	Restormel	216553	69916	167.21	1435	0.522	0.92	0.035	1.006	0.525	48011
48801	Fowey	Restormel	168391	33697	26.53	1265	0.672	0.976	0.0351	0.753	0.292	48801
48802	Fowey	Restormel	174808	42128	42.69	1148	0.615	0.909	0.0165	0.722	0.168	48802
48803	Fowey	Restormel	173849	42260	33.62	1161	0.623	0.984	0.0214	0.807	0.243	48803
49001	Camel	Denby	207824	73231	209.94	1338	0.555	0.987	0.0338	1.142	0.402	49001
49002	Hayle	St Erth	159925	32469	48.51	1076	0.642	0.977	0.0264	0.743	0.257	49002
49003	De Lank	De Lank	215420	78115	21.61	1628	0.379	0.998	0.0636	0.848	0.663	49003
49004	Gannel	Gwills	186166	57381	40.83	1046	0.617	0.999	0.0254	0.895	0.267	49004
50001	Taw	Umberleigh	272169	117345	832.97	1153	0.472	0.997	0.0374	0.888	0.531	50001
50002	Torridge	Torrington	248590	107223	664.23	1185	0.425	0.996	0.0496	0.935	0.742	50002
50005	West Okement	Vellake	258022	87659	13.37	2066	0.349	0.981	0.0143	0.733	0.223	50005
50006	Mole	Woodleigh	274173	128743	326.99	1306	0.502	0.999	0.0316	0.805	0.429	50006
50007	Taw	Taw Bridge	264734	97339	72.16	1226	0.49	0.994	0.046	0.902	0.557	50007
50008	Lew	Gribbleford Bridge	250125	98332	71.18	1192	0.406	0.999	0.0438	0.794	1.002	50008
50009	Lew	Norley Bridge	247497	98926	20.16	1195	0.446	1	0.0231	0.785	0.28	50009
50010	Torridge	Rockhay Bridge	238420	112315	258.42	1231	0.399	0.997	0.0487	0.894	0.66	50010
50011	Okement	Jacobstowe	258914	93284	80.2	1509	0.478	0.981	0.0299	0.804	0.436	50011
50012	Yeo	Veraby	282141	128002	53.88	1316	0.461	1	0.0375	0.753	0.432	50012
50801	Yeo	Parkham	237300	122071	7.51	1238	0.47	1	0.0023	9.999	0.023	50801
51001	Doniford Stream	Swill Bridge	309710	137415	74.22	911	0.629	0.988	0.0381	0.514	0.353	51001
51002	Horner Water	West Luccombe	287466	143161	20.38	1485	0.539	0.978	0.0028	9.999	0.038	51002
51003	Washford	Beggearn Huish	300447	136965	36.7	1151	0.588	0.982	0.0048	9.999	0.058	51003
52003	Halsewater	Halsewater	315396	130295	88.25	851	0.625	0.991	0.0666	0.522	0.572	52003
52004	Isle	Ashford Mill	334328	113224	87.41	891	0.499	0.979	0.0837	0.589	0.705	52004
52005	Tone	Bishops Hull	310309	124174	203.65	964	0.562	0.977	0.0537	0.539	0.524	52005
52006	Yeo	Pen Mill	359794	112721	216.18	865	0.569	0.965	0.0722	0.879	0.588	52006
52007	Parrett	Chiselborough	347217	110232	74.26	886	0.537	1	0.0665	0.806	0.564	52007
52010	Brue	Lovington	367131	135772	137.79	866	0.527	0.997	0.0815	0.608	0.629	52010
52011	Cary	Somerton	355533	128169	84.62	715	0.532	1	0.2355	1.03	1.478	52011
52014	Tone	Greenham	304516	127449	57.67	1101	0.553	0.937	0.0111	0.602	0.134	52014
52015	Land Yeo	Wraxall Bridge	351546	169292	23.33	906	0.669	0.933	0.0579	0.678	0.442	52015
52016	Currypool Stream	Currypool Farm	318469	137311	15.7	934	0.586	1	0.0375	0.435	0.394	52016
52025	Hillfarrance	Milverton	308310	128522	27.75	1009	0.633	0.996	0.023	0.59	0.227	52025
53002	Semington Brook	Semington	397337	157744	153.39	712	0.564	0.987	0.1214	0.787	0.705	53002
53004	Chew	Compton Dando	357940	160244	128.9	987	0.591	0.842	0.045	0.903	0.383	53004
53007	Frome(Somerset)	Tellisford	373521	146516	263.74	965	0.563	0.96	0.0545	0.899	0.506	53007
53008	Avon	Great Somerford	388259	186712	305.19	804	0.622	0.988	0.0931	0.874	0.607	53008
53013	Marden	Stanley	401470	172405	99.34	724	0.559	0.98	0.073	1.017	0.477	53013
53017	Boyd	Bitton	371777	175065	47.71	806	0.497	0.998	0.0503	1.035	0.424	53017
53018	Avon	Bathford	385923	166414	1569.29	817	0.575	0.985	0.0961	1.029	0.731	53018
53025	Mells	Vallis	367966	146969	118.05	1056	0.656	0.943	0.0453	1.058	0.358	53025

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
53028	By Brook	Middlehill	380982	174546	100.76	835	0.726	0.999	0.0315	1.01	0.226	53028
54001	Severn	Bewdley	336743	309876	4329.83	912	0.541	0.973	0.1055	0.941	1.172	54001
54005	Severn	Montford	310947	306938	2026.73	1147	0.47	0.977	0.0919	0.719	1.344	54005
54008	Teme	Tenbury	340470	281430	1124.59	841	0.612	0.994	0.0635	0.85	0.662	54008
54012	Tern	Walcot	363754	325596	851.65	694	0.616	0.966	0.1636	0.979	1.172	54012
54014	Severn	Abermule	300201	289855	574.66	1256	0.449	0.97	0.0598	0.822	0.847	54014
54016	Roden	Rodington	351699	328761	261.94	693	0.615	0.981	0.2212	1.085	1.38	54016
54018	Rea Brook	Hookagate	336296	305670	173.1	757	0.508	0.991	0.0756	0.859	0.576	54018
54020	Perry	Yeaton	337381	328873	188.05	739	0.654	0.954	0.19	1.02	1.427	54020
54022	Severn	Plynlimon flume	283246	288071	8.69	2483	0.323	1	0.0098	0.8	0.132	54022
54025	Dulas	Rhos-y-pentref	296856	278995	53.17	1268	0.439	1	0.024	0.965	0.263	54025
54028	Vyrnwy	Llanymynech	307738	318661	778.96	1339	0.439	0.969	0.0519	0.817	0.814	54028
54029	Teme	Knightsford Bridge	346634	279096	1483.65	818	0.6	0.994	0.0618	0.901	0.74	54029
54034	Dowles Brook	Oak Cottage	372015	276775	42.1	715	0.632	0.997	0.0117	0.878	0.134	54034
54036	Isbourne	Hinton on the Green	403964	231915	92.75	701	0.479	0.99	0.0694	0.596	0.543	54036
54038	Tanat	Llanyblodwel	312711	327199	240.98	1274	0.476	0.996	0.0382	0.829	0.529	54038
54040	Meese	Tibberton	375818	322857	159.94	700	0.588	0.931	0.1125	0.992	0.809	54040
54041	Tern	Eaton On Tern	367078	333733	193.51	719	0.645	0.954	0.1198	0.9	0.999	54041
54044	Tern	Ternhill	372032	336285	95.66	739	0.698	0.96	0.1004	0.861	0.812	54044
54102	Avon	Lilbourne	462407	279063	109.57	668	0.354	0.906	0.0951	0.775	0.704	54102
54106	Stour	Shipston	424857	236671	185.16	677	0.454	0.993	0.0417	0.764	0.374	54106
55002	Wye	Belmont	306152	255938	1894.26	1230	0.472	0.967	0.0693	0.695	1.607	55002
55003	Lugg	Lugwardine	338685	257804	885.11	813	0.588	0.99	0.1064	0.775	1.034	55003
55004	Irfon	Abernant	284965	252743	73.06	1845	0.402	1	0.0287	0.658	0.459	55004
55005	Wye	Rhayader	291753	277164	164.46	1656	0.419	0.997	0.0414	0.913	0.619	55005
55007	Wye	Erwood	298496	263086	1283.4	1386	0.426	0.96	0.0412	0.894	0.612	55007
55011	Ithon	Llandewi	309350	277914	110.47	1086	0.395	0.999	0.0283	0.775	0.338	55011
55012	Irfon	Cilmery	289393	250197	246.4	1627	0.431	0.997	0.0418	0.789	0.611	55012
55013	Arrow	Titley Mill	323594	254543	125.92	962	0.553	0.999	0.0382	0.742	0.4	55013
55014	Lugg	Byton	324892	265277	202.54	977	0.593	0.996	0.0646	0.67	0.633	55014
55021	Lugg	Butts Bridge	334076	264541	365.9	877	0.61	0.992	0.0902	0.658	0.812	55021
55022	Trothy	Mitchel Troy	341042	214581	141.9	887	0.572	0.998	0.0451	0.909	0.445	55022
55023	Wye	Redbrook	326244	248366	4016.42	1010	0.542	0.979	0.0824	0.857	1.392	55023
55025	Llynfi	Three Cocks	312742	232028	131.51	999	0.576	0.95	0.0367	0.889	0.348	55025
55026	Wye	Ddol Farm	292074	276803	172.17	1636	0.423	0.997	0.041	0.92	0.613	55026
55029	Monnow	Grosmont	334942	231598	355.07	956	0.583	0.997	0.0723	0.788	0.745	55029
56001	Usk	Chain Bridge	308051	225004	913.2	1367	0.597	0.98	0.0445	0.783	0.769	56001
56003	Honddu	The Forge Brecon	302453	237135	62.5	1171	0.528	0.999	0.0268	0.907	0.325	56003
56004	Usk	Llandetty	297278	229567	545.59	1478	0.547	0.974	0.037	0.865	0.547	56004
56006	Usk	Trallong	288960	227656	184.74	1674	0.477	0.963	0.0365	0.865	0.511	56006
56007	Senni	Pont Hen Hafod	292742	221883	19.31	1974	0.495	1	0.0432	0.776	0.573	56007
56013	Yscir	Pontaryscir	297621	238443	63.26	1299	0.494	1	0.0256	0.963	0.342	56013
57015	Taff	Merthyr Tydfil	302335	214033	111.18	1858	0.352	0.85	0.0273	0.807	0.374	57015
58002	Neath	Resolven	290201	210206	190.8	1946	0.346	0.983	0.0428	0.831	0.637	58002
58006	Mellte	Pontneddfechan	294644	214977	65.35	1981	0.322	0.975	0.0297	0.913	0.41	58006
58010	Hepste	Esgair Carnau	297141	216070	10.94	2079	0.261	1	0.0397	0.917	0.557	58010
58012	Afan	Marcroft Weir	284377	196842	89.42	2038	0.451	1	0.0172	0.613	0.298	58012
59001	Tawe	Ynystanglws	277704	212026	227.46	1890	0.407	0.996	0.0504	0.771	0.902	59001

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
59002	Loughor	Tir-y-dail	261859	216026	46.28	1500	0.467	0.998	0.0535	0.703	0.633	59002
60001	Loughor	Tir-y-dail	269002	235626	1090.83	1535	0.478	0.984	0.0607	0.767	1.321	60001
60002	Cothi	Felin Mynachdy	260063	237727	298.73	1551	0.5	0.997	0.0315	0.974	0.48	60002
60003	Taf	Clog-y-Fran	218991	222325	216.48	1420	0.553	0.999	0.0505	0.741	0.671	60003
60005	Bran	Llandovery	281412	241032	63.71	1489	0.485	0.997	0.0494	0.548	0.581	60005
60006	Gwili	Glangwili	240908	229292	131.05	1603	0.536	0.999	0.0295	0.837	0.447	60006
60010	Tywi	Nantgaredig	268978	235608	1092.13	1534	0.478	0.984	0.061	0.766	1.33	60010
60013	Cothi	Pont Ynys Brechfa	262036	239779	243.04	1538	0.493	0.997	0.0336	0.934	0.478	60013
61001	Western Cleddau	Prendergast Mill	195048	226904	197.8	1276	0.56	0.996	0.0444	0.948	0.557	61001
61002	Eastern Cleddau	Canaston Bridge	208851	224685	181.9	1437	0.537	0.967	0.0414	0.83	0.55	61002
62001	Teifi	Glan Teifi	248986	248171	897.26	1379	0.507	0.995	0.0485	1.168	0.757	62001
62002	Teifi	Llanfair	259932	253698	517.56	1392	0.484	0.993	0.0619	1.043	0.846	62002
63001	Ystwyth	Pont Llolwyn	271615	274267	174.54	1445	0.491	0.99	0.0462	0.772	0.69	63001
63002	Rheidol	Llanbadarn Fawr	274413	283210	181.88	1756	0.435	0.898	0.0537	0.709	0.977	63002
64001	Dyfi	Dyfi Bridge	284140	306844	464.65	1835	0.478	0.995	0.0292	0.763	0.534	64001
64002	Dysynni	Pont-y-Garth	269100	309379	74.93	2166	0.448	0.951	0.0551	0.624	0.814	64002
65001	Glaslyn	Beddgelert	261419	351185	67.14	2809	0.406	0.896	0.0487	0.844	1.721	65001
65004	Gwyrfai	Bontnewydd	255039	356469	46.12	2153	0.412	0.862	0.0655	0.857	0.974	65004
65005	Erch	Pencaenewydd	239274	343245	19.39	1477	0.439	0.991	0.0711	0.955	0.78	65005
65006	Seiont	Peblig Mill	257847	360309	79.92	2258	0.499	0.85	0.0622	0.781	1.46	65006
65007	Dwyfawr	Garndolbenmaen	253671	345658	51.56	2056	0.404	0.968	0.0558	0.677	0.761	65007
66001	Clwyd	Pont-y-Cambwll	309229	360668	404.67	910	0.588	0.993	0.057	0.707	0.518	66001
66002	Elwy	Pant yr Onen	291474	365507	218.53	1145	0.483	0.979	0.0339	0.902	0.406	66002
66004	Wheeler	Bodfari	315144	371478	62.9	863	0.696	0.975	0.028	0.978	0.191	66004
66005	Clwyd	Ruthin Weir	309816	351808	96.37	958	0.518	0.995	0.0371	0.733	0.348	66005
66006	Elwy	Pont-y-Gwyddel	290505	364668	191.38	1185	0.476	0.98	0.0318	0.897	0.366	66006
66011	Conwy	Cwm Llanerch	278217	352151	341.76	2040	0.363	0.976	0.0461	0.903	0.754	66011
67003	Brenig	Llyn Brenig outflow	297273	356836	22.44	1317	0.319	0.983	0.0182	1.072	0.154	67003
67005	Ceiriog	Brynkinalt Weir	317503	336107	111.76	1198	0.462	1	0.0231	0.783	0.337	67005
67006	Alwen	Druid	296649	349512	185.66	1305	0.403	0.897	0.0381	0.846	0.466	67006
67008	Alyn	Pont-y-Capel	323018	359064	225.76	917	0.591	0.99	0.048	0.865	0.442	67008
67009	Alyn	Rhydymwyn	319019	357784	81.6	968	0.615	0.99	0.0328	1.068	0.322	67009
67010	Gelyn	Cynefail	283514	343508	12.87	2000	0.251	0.969	0.0322	0.703	0.458	67010
67013	Hirnant	Plas Rhiwedog	296006	331068	32.47	1756	0.415	1	0.0182	0.682	0.26	67013
67015	Dee	Manley Hall	303096	340023	1008.74	1367	0.431	0.934	0.0457	0.963	0.741	67015
67019	Tryweryn	Weir X	286121	340437	110.98	1840	0.312	0.982	0.0448	0.92	0.624	67019
67020	Dee	Chester Weir	317403	345370	1800.92	1110	0.471	0.959	0.0819	0.697	1.115	67020
68001	Weaver	Ashbrook	365235	350689	621.52	732	0.513	0.955	0.1575	0.977	1.185	68001
68005	Weaver	Audlem	359817	344402	201.44	719	0.502	0.95	0.1593	1.021	1.101	68005
68006	Dane	Hulme Walfield	394080	365348	149.89	1019	0.414	0.979	0.0488	0.697	0.642	68006
68007	Wincham Brook	Lostock Gralam	375827	376264	148.28	818	0.508	0.942	0.1816	0.883	1.229	68007
68011	Arley Brook	Gore Farm	366591	381600	33.76	831	0.437	0.998	0.2498	0.907	1.758	68011
68020	Gowy	Bridge Trafford	351374	364258	148.7	729	0.538	0.994	0.1466	0.887	1.026	68020
68044	Dane	Hugbridge	398633	367268	72.57	1160	0.373	0.997	0.0251	0.78	0.362	68044
69017	Goyt	Marple Bridge	402590	382527	184.23	1152	0.482	0.918	0.0304	0.846	0.463	69017
71006	Ribble	Henthorn	380310	457753	446.28	1343	0.367	0.997	0.0906	0.937	2.348	71006
71008	Hodder	Hodder Place	366843	450185	258.14	1602	0.33	0.97	0.0549	0.864	0.843	71008
71011	Ribble	Arnford	381225	469050	203.22	1446	0.382	0.998	0.0987	0.731	3.793	71011

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
72002	Wyre	St Michaels	354179	445967	273.84	1251	0.368	0.958	0.1369	0.551	1.452	72002
72004	Lune	Caton	366470	482803	985.37	1521	0.404	0.997	0.0689	0.779	1.259	72004
72005	Lune	Killington New Bridge	362069	503090	219.21	1670	0.438	0.995	0.0483	0.975	0.703	72005
72006	Lune	Kirkby Lonsdale	366219	495009	510.02	1652	0.425	0.997	0.0515	0.85	0.863	72006
72007	Brock	U/S A6	356440	444787	31.53	1361	0.319	1	0.0535	0.802	0.605	72007
72011	Rawthey	Brigg Flatts	372441	490983	194.15	1751	0.348	0.999	0.0372	0.759	0.597	72011
72014	Conder	Galgate	351620	459069	28.99	1183	0.443	0.975	0.0822	0.748	0.917	72014
72015	Lune	Lunes Bridge	363046	505307	140.83	1630	0.44	0.993	0.0549	0.823	0.7	72015
72016	Wyre	Scorton Weir	356552	454584	88	1473	0.316	0.942	0.0461	0.709	0.624	72016
73002	Crake	Low Nibthwaite	329406	495149	72.9	2147	0.363	0.73	0.0518	0.835	0.65	73002
73003	Kent	Burneside	346201	501646	74.22	1897	0.464	0.945	0.0629	0.808	0.858	73003
73005	Kent	Sedgwick	350609	499239	212.19	1726	0.514	0.976	0.0739	0.832	1.091	73005
73006	Cunsey Beck	Eel House Bridge	335298	497431	18.77	1897	0.448	0.727	0.0522	0.891	0.644	73006
73008	Bela	Beetham	355394	484836	127.45	1294	0.529	0.952	0.093	0.77	0.861	73008
73009	Sprint	Sprint Mill	349722	503242	34.8	2011	0.453	0.997	0.0612	0.735	1.069	73009
73010	Leven	Newby Bridge FMS	335814	501830	247.81	2172	0.44	0.694	0.0524	0.972	0.797	73010
73011	Mint	Mint Bridge	355566	498624	65.59	1599	0.513	0.993	0.0617	0.836	0.748	73011
73012	Mint	Mint Bridge	350452	500547	183.23	1787	0.496	0.972	0.0714	0.761	1.034	73012
74001	Duddon	Duddon Hall	321459	496418	86.01	2261	0.338	0.985	0.0465	0.866	0.794	74001
74002	Irt	Galesyke	317603	508084	43.99	2629	0.367	0.746	0.0281	0.855	0.542	74002
74003	Ehen	Bleach Green	314176	513743	44.58	2542	0.417	0.74	0.0321	0.898	0.524	74003
74005	Ehen	Braystones	307113	515094	129.49	1753	0.497	0.897	0.0648	0.783	0.995	74005
74006	Calder	Calder Hall	308073	509763	43.93	1828	0.423	0.999	0.0314	0.603	0.447	74006
74007	Esk	Cropple How	319331	501761	70.11	2307	0.417	0.964	0.0585	0.73	0.961	74007
74008	Duddon	Ulpha	323909	499065	48.05	2507	0.325	0.974	0.0482	0.713	0.785	74008
75002	Derwent	Camerton	321058	523737	661.92	1810	0.438	0.844	0.0746	0.878	1.38	75002
75003	Derwent	Ouse Bridge	327778	521979	363.01	2064	0.439	0.789	0.0768	0.759	1.478	75003
75004	Cocker	Southwaite Bridge	316121	520975	116.17	1976	0.483	0.83	0.0486	0.672	0.748	75004
75005	Derwent	Portinscale	330425	519655	237.26	2238	0.408	0.846	0.0627	0.748	1.353	75005
75007	Glenderamackin	Threlkeld	335872	526349	64.57	1723	0.394	0.999	0.0523	0.88	0.646	75007
75009	Greta	Low Briery	333182	522356	146.97	2025	0.399	0.91	0.0522	0.795	0.834	75009
75017	Ellen	Bullgill	319601	538599	102.4	1106	0.488	0.982	0.0719	0.816	0.783	75017
76001	Haweswater Beck	Burnbanks	347035	513023	32.34	2438	0.345	0.645	0.0154	0.869	0.258	76001
76002	Eden	Warwick Bridge	360654	522445	1374.83	1272	0.509	0.955	0.0618	0.919	0.968	76002
76003	Eamont	Udford	346478	519218	407.17	1768	0.453	0.86	0.0623	0.798	1.03	76003
76004	Lowther	Eamont Bridge	350892	515622	156.2	1828	0.406	0.901	0.0553	0.828	0.845	76004
76005	Eden	Temple Sowerby	371161	515038	618.21	1142	0.474	0.998	0.06	0.825	0.725	76005
76007	Eden	Sheepmount	355830	534240	2276.03	1182	0.489	0.971	0.0741	0.826	1.071	76007
76008	Irthing	Greenholme	359554	566485	333.43	1073	0.359	0.994	0.0672	0.954	0.802	76008
76010	Petteril	Harraby Green	346101	539276	157.63	940	0.59	0.993	0.0769	0.973	0.699	76010
76011	Coal Burn	Coalburn	369386	578507	1.63	1096	0.196	1	0.0736	0.865	0.702	76011
76014	Eden	Kirkby Stephen	378419	503113	66.84	1492	0.409	1	0.0297	0.745	0.37	76014
76015	Eamont	Pooley Bridge	340740	517213	149.24	2150	0.404	0.743	0.0382	0.877	0.696	76015
76806	Eamont	Pooley Bridge	379229	508221	223.1	1270	0.443	0.997	0.0472	0.682	0.549	76806
76809	Eamont	Pooley Bridge	336376	538876	248.51	1213	0.419	0.998	0.0781	0.803	0.905	76809
76810	Eamont	Pooley Bridge	360686	522369	1371.7	1273	0.509	0.955	0.0615	0.921	0.962	76810
76811	Eamont	Pooley Bridge	341782	525858	33.97	1428	0.457	0.999	0.0724	0.97	0.797	76811
77002	Esk	Canonbie	331203	593560	495.37	1423	0.405	0.994	0.035	0.925	0.568	77002

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
77003	Liddel Water	Rowanburnfoot	350113	591271	319.3	1291	0.314	1	0.0333	0.839	0.605	77003
78003	Annan	Brydekirk	310271	593596	925.03	1350	0.486	0.989	0.0769	0.795	1.098	78003
78004	Kinnel Water	Redhall	304389	597392	76.17	1466	0.431	0.999	0.0598	0.695	0.769	78004
78005	Kinnel Water	Bridgemuir	301516	593948	229.26	1397	0.434	0.996	0.0776	0.622	0.986	78005
79002	Nith	Friars Carse	276757	605289	797.71	1461	0.433	0.991	0.05	0.856	0.838	79002
79003	Nith	Hall Bridge	260365	610481	155.76	1512	0.357	0.973	0.0664	0.794	0.892	79003
79004	Scar Water	Capenoch	276657	598774	142.76	1627	0.446	0.999	0.0319	0.883	0.499	79004
79005	Cluden Water	Fiddlers Ford	279568	586238	237.23	1422	0.497	0.985	0.0622	0.836	0.87	79005
79006	Nith	Drumlanrig	272065	610779	468.87	1485	0.386	0.99	0.0408	1.052	0.617	79006
80001	Urr	Dalbeattie	277424	573857	197.07	1341	0.376	0.963	0.0714	0.915	0.822	80001
81002	Cree	Newton Stewart	237614	579409	366.25	1757	0.341	0.932	0.0697	0.91	0.973	81002
81003	Luce	Airyhemming	216030	569848	170.87	1503	0.296	0.977	0.0584	0.968	0.753	81003
82001	Girvan	Robstone	234068	602995	243.63	1368	0.4	0.942	0.0547	0.893	0.741	82001
82003	Stinchar	Balnowlart	224449	587731	324.54	1507	0.392	0.987	0.0613	0.935	0.843	82003
83003	Ayr	Catrine	265666	627979	167.21	1292	0.327	0.991	0.0455	0.819	0.592	83003
83005	Irvine	Shewalton	249486	638573	367.59	1228	0.339	0.98	0.0813	0.823	0.9	83005
83006	Ayr	Mainholm	256485	622724	579.08	1212	0.33	0.992	0.0582	0.88	0.726	83006
83802	Ayr	Mainholm	252528	636317	212	1222	0.348	0.986	0.0705	0.807	0.776	83802
84002	Calder	Muirshiel	228550	664723	12.06	2316	0.271	0.988	0.0398	0.825	0.546	84002
84003	Clyde	Hazelbank	293281	631849	1093	1165	0.45	0.97	0.0645	0.818	0.851	84003
84004	Clyde	Sills of Clyde	295915	628161	741.79	1224	0.458	0.964	0.0624	0.751	0.877	84004
84005	Clyde	Blairston	286797	637116	1699.42	1139	0.422	0.959	0.0643	0.88	0.843	84005
84009	Nethan	Kirkmuirhill	278224	637191	67.08	1194	0.41	0.976	0.0345	0.712	0.4	84009
84011	Gryfe	Craigend	232559	668504	86.87	1837	0.449	0.93	0.0759	0.872	0.921	84011
84014	Avon Water	Fairholm	268831	641740	263.01	1264	0.376	0.986	0.0568	0.974	0.618	84014
84017	Black Cart Water	Milliken Park	234786	659866	103.14	1790	0.445	0.786	0.0545	0.862	0.637	84017
84018	Clyde	Tulliford Mill	293415	628983	938.48	1204	0.452	0.966	0.0616	0.786	0.86	84018
84020	Glazert Water	Milton of Campsie	261408	679737	51.9	1561	0.414	0.991	0.0525	0.72	0.597	84020
85001	Leven	Linnbrane	240563	696549	786.1	2023	0.436	0.681	0.0549	0.837	1.232	85001
85002	Endrick Water	Gaidrew	255288	685415	219.24	1484	0.454	0.981	0.0632	0.758	0.781	85002
85003	Falloch	Glen Falloch	232804	722140	79.62	2848	0.379	0.988	0.028	0.844	0.45	85003
86001	Little Eachaig	Dalinlongart	211516	681123	31.84	2340	0.393	1	0.027	0.917	0.423	86001
86002	Eachaig	Eckford	212329	694237	138.63	2470	0.379	0.836	0.0327	0.804	0.598	86002
89804	Eachaig	Eckford	218044	733253	37.38	2766	0.362	0.995	0.0468	0.713	1.23	89804
91802	Allt Leachdach	intake	226882	776150	6.52	2555	0.397	0.992	0.0031	9.999	0.041	91802
93001	Carron	New Kelso	202131	848740	139.13	2616	0.406	0.858	0.0478	0.675	0.845	93001
94001	Ewe	Poolewe	199247	866278	441.1	2273	0.365	0.664	0.0381	1.032	0.61	94001
95001	Inver	Little Assynt	223040	922196	138.5	2207	0.399	0.67	0.0345	0.985	0.491	95001
96001	Halladale	Halladale	289289	947524	193.75	1096	0.297	0.955	0.0741	0.934	0.785	96001
96002	Naver	Apigill	260919	936914	474.08	1383	0.338	0.822	0.0698	0.911	0.955	96002
96003	Strathy	Strathy Bridge	280908	953653	120.87	1090	0.289	0.895	0.0736	0.953	0.793	96003
96004	Strathmore	Allnabad	242592	941764	105.31	2456	0.352	0.938	0.0413	0.789	0.637	96004
97002	Thurso	Halkirk	307125	945990	414.39	1058	0.292	0.861	0.1083	0.817	1.069	97002
201002	Fairywater	Dudgeon Bridge	45100	540100	158.22	1285	0.419	0.992	0.1244	0.822	1.366	201002
201005	Camowen	Camowen Terrace	69300	533200	276.57	1144	0.514	0.989	0.0799	0.926	0.81	201005
201006	Drumragh	Campsie Bridge	54500	526600	319.94	1163	0.441	0.998	0.0991	0.903	0.98	201006
201007	Burn Dennet	Burndennet	61300	565000	147.14	1186	0.455	0.994	0.046	0.752	0.515	201007
201008	Derg	Castlederg	27500	547900	335.39	1558	0.504	0.914	0.0771	0.887	0.907	201008

No.	River	Gauging station	Easting	Northing	AREA [km^2]	SAAR [mm]	BFIHOST [-]	FARL [-]	FPEXT	FPLOC	FPDBAR [cm]	No.
201009	Owenkillew	Crosh	72100	550500	440.5	1367	0.355	0.997	0.0441	0.963	0.509	201009
201010	Mourne	Drumnabuoy House	54700	542000	1844.19	1288	0.448	0.977	0.0787	0.994	0.891	201010
202001	Roe	Ardnargle	86100	573500	365.69	1250	0.403	0.993	0.0595	0.786	0.705	202001
202002	Faughan	Drumahoe	70300	570100	273.03	1219	0.426	1	0.0411	0.896	0.477	202002
203010	Blackwater	Maydown Bridge	77000	507400	964.93	1008	0.395	0.976	0.1004	0.937	1.096	203010
203011	Maine	Dromona	125400	573800	243.54	1205	0.492	0.993	0.1291	0.846	1.192	203011
203012	Ballinderry	Ballinderry Bridge	91100	538000	429.2	1077	0.523	0.996	0.091	0.889	0.787	203012
203018	Six-Mile Water	Antrim	139900	545000	277.83	1075	0.425	0.993	0.0894	0.881	0.871	203018
203019	Claudy	Glenone Bridge	102600	564500	126.36	1131	0.463	0.992	0.1523	0.769	1.307	203019
203020	Moyola	Moyola New Bridge	95400	554600	304.23	1225	0.454	0.992	0.1121	0.729	1.068	203020
203022	Blackwater	Derrymeen Bridge	64600	515200	183.49	1143	0.46	0.977	0.086	0.844	0.883	203022
203024	Cusher	Gamble's Bridge	108100	494600	170.94	995	0.365	0.992	0.0583	0.85	0.559	203024
203026	Glenavy	Glenavy	133400	529000	44.59	987	0.376	0.939	0.0894	0.893	0.855	203026
203027	Braid	Ballee	133500	564700	183	1202	0.498	0.994	0.0888	0.753	0.907	203027
203028	Agivey	Whitehill	97000	574300	100.33	1270	0.404	0.999	0.0928	0.867	1.048	203028
203033	Upper Bann	Bannfield	133300	486500	101.64	1261	0.471	0.951	0.0616	0.673	0.545	203033
203039	Clogh	Tullynewey	130000	571900	98.37	1296	0.437	0.986	0.0742	0.747	0.756	203039
203042	Crumlin	Cidercourt Bridge	133600	533900	54.47	991	0.338	1	0.0913	0.814	0.691	203042
203043	Oonawater	Shanmoy	83400	520300	88.59	1003	0.4	0.974	0.0776	0.936	0.767	203043
203046	Rathmore Burn	Rathmore Bridge	133300	546800	22.51	1043	0.43	1	0.0726	0.77	0.601	203046
203049	Clady	Clady Bridge	138000	536800	29.38	1079	0.367	1	0.0599	0.818	0.502	203049
203093	Maine	Shane's Viaduct	128800	564600	710.96	1153	0.458	0.995	0.1129	0.91	1.13	203093
204001	Bush	Seneirl Bridge	120800	590800	298.98	1116	0.561	0.992	0.164	0.79	1.551	204001
205005	Ravernet	Ravernet	143900	515600	73.53	947	0.422	0.934	0.1065	1.047	0.892	205005
205008	Lagan	Drumiller	137300	505200	84.98	1016	0.403	0.992	0.0694	0.751	0.669	205008
205011	Annacloy	Kilmore Bridge	148500	509400	186.31	968	0.44	0.96	0.1043	0.933	0.896	205011
206001	Clanrye	Mountmill Bridge	123400	488200	120.54	975	0.568	0.972	0.064	0.901	0.513	206001
206004	Bessbrook	Carnbane	112900	486400	34.76	1055	0.584	0.917	0.0441	0.975	0.408	206004
206006	Bessbrook	Carnbane	142200	481400	13.66	1720	0.336	0.98	0.0236	0.791	0.298	206006
236005	Colebrooke	Ballindarragh Bridge	51300	508200	313.59	1156	0.421	0.987	0.0821	0.81	0.883	236005
236007	Sillees	Drumrainey Bridge	22600	515000	166.3	1332	0.495	0.888	0.1621	0.844	2.281	236007

Appendix C GLS regression details

This appendix contains a description of the recursive procedure used in the exploratory analysis of a suitable description of the model error correlation. The procedure includes a re-weighting of the raw regression residuals to a set of new residuals with a covariance structure essentially similar to the model error covariance.

Model Description

To relate the index flood variable from N different catchments to a set of catchment descriptors, consider a vector of sample (log transformed) median annual maximum floods, $\mathbf{y}$, where individual sites are denoted with a subscript i. Each sample value y_i is described in terms of a population regression model and two individual error components representing the sampling, ε_i, and modelling, η_i, errors respectively, so that

$$y_i = \mathbf{x}_i^T \boldsymbol{\theta} + \eta_i + \varepsilon_i = \mathbf{x}_i^T \boldsymbol{\theta} + \omega_i ,$$

where $\boldsymbol{\theta}$ is a vector of regression model parameters and x_i is a vector of catchment descriptors with a value of one in the first location. The covariance of the sampling errors is denoted by $\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}$, the corresponding covariance of the modelling errors is denoted $\boldsymbol{\Sigma}_{\boldsymbol{\eta}}$, and the two errors are assumed mutually independent. Further, it is assumed that the elements along the diagonal of the modelling error covariance are identical and equal to σ_η^2. In pioneering the use of the GLS procedure in hydrology, Tasker and Stedinger (1989) assumed the modelling covariance matrix to be of the form $\boldsymbol{\Sigma}_{\boldsymbol{\eta}} = \sigma_\eta^2 \mathbf{I}$. Thus they made the specific assumption that there is no cross correlation between the modelling errors. In contrast, the model formulated here assumes the cross correlation to be represented by the associated modelling error correlation matrix $\mathbf{R}_{\boldsymbol{\eta}}$, so that

$$\boldsymbol{\Sigma}_{\boldsymbol{\eta}} = \sigma_\eta^2 \mathbf{R}_{\boldsymbol{\eta}} .$$

While estimates of the sampling error covariance can be obtained directly from the dataset, the covariance of the modelling errors has to be estimated as part of a recursive procedure. From an initial guess of the modelling error covariance, a set of regression residuals can be estimated. By re-weighting these residuals, it is possible to obtain a set of GLS residuals from which the modelling error variance can be estimated. By further re-weighting the GLS residuals, an estimate of the modelling error correlation matrix can be obtained. These recursive estimates can then be used to estimate a new regression model and a new set of regression residuals. This procedure is continued until the modelling error variance σ_η^2 has converged.

The first step in the recursive procedure is to define the covariance matrix of the vector of total errors as

$$E\left\{\boldsymbol{\omega}\boldsymbol{\omega}^{\mathbf{T}}\right\} = \boldsymbol{\Sigma}_{\boldsymbol{\omega}} = \boldsymbol{\Sigma}_{\boldsymbol{\eta}} + \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}} = \sigma_\eta^2 \left(\mathbf{R}_{\boldsymbol{\eta}} + \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}} \big/ \sigma_\eta^2\right) = \sigma_\eta^2 \mathbf{G} . \tag{C.1}$$

To implement the procedure, the expression in equation (C.1) is interpreted as representing the covariance of the total error in terms of σ_η^2, being the value to be estimated from the present step of the recursive procedure, and of $\mathbf{G}$, a known matrix derived from values of σ_η^2 and $\mathbf{R}_\eta$, which are either initial guesses or the estimates obtained in the previous step. In the expressions developed below, equation (C.1) is taken temporarily to be valid even though an estimated value of $\mathbf{G}$ is used.

It can be shown that the individual estimates of the overall residuals, $\hat{\omega}_i$, can be expressed in terms of the true underlying residuals as

$$\hat{\boldsymbol{\omega}} = \mathbf{V}\boldsymbol{\omega}, \quad \mathbf{V} = \mathbf{I} - \mathbf{X}\left(\mathbf{X}^T\mathbf{G}^{-1}\mathbf{X}\right)^{-1}\mathbf{X}^T\mathbf{G}^{-1}.$$

This enables the covariance matrix of the estimated regression residuals to be represented as

$$\boldsymbol{\Sigma}_{\hat{\boldsymbol{\omega}}} = E\left\{\hat{\boldsymbol{\omega}}\hat{\boldsymbol{\omega}}^T\right\} = \sigma_\eta^2\left[\mathbf{G} - \mathbf{X}\left(\mathbf{X}^T\mathbf{G}^{-1}\mathbf{X}\right)\mathbf{X}^T\right].$$

GLS residuals

For Generalised Least Squares analysis, it is common to work with an alternative set of sample residuals, the GLS residuals. These residuals, $\tilde{\boldsymbol{\omega}}$, can be related to the "raw" sample residuals, $\hat{\boldsymbol{\omega}}$, in the following way. A matrix-square-root of the scaled covariance matrix $\mathbf{G}$ is first required, and it convenient to work with the Cholesky decomposition

$$\mathbf{G} = \mathbf{U}_\mathbf{G}^\mathbf{T}\mathbf{U}_\mathbf{G}, \qquad \text{(C.2)}$$

where $\mathbf{U}_\mathbf{G}$ is an upper triangular matrix. The sample GLS residuals are defined as

$$\tilde{\boldsymbol{\omega}} = \mathbf{U}_\mathbf{G}^{-\mathbf{T}}\hat{\boldsymbol{\omega}} = \mathbf{U}_\mathbf{G}^{-\mathbf{T}}\left(\mathbf{y} - \hat{\mathbf{y}}\right).$$

Given the assumption that the value of $\mathbf{G}$ temporarily being used is correct, an unbiased estimate of σ_η^2 is provided by

$$\hat{\sigma}_\eta^2 = \left(N - p\right)^{-1}\sum_{i=1}^{N}\tilde{\omega}_i^2$$

and, given the assumption, this is the minimum variance unbiased estimate for σ_η^2. The estimated value of σ_η^2 can then be carried forward to the next step of the recursion. Here N is the number of catchments and p is the number of regressors (including the constant term).

Re-weighted GLS

To obtain an estimate of the modelling error correlation matrix $\mathbf{R}_\eta$, a re-weighted version of the GLS residuals is constructed: these can also be considered as a re-weighting of the raw residuals. In parallel with equation (C.2), a Cholesky decomposition of the correlation matrix is constructed, so that

$$\mathbf{R}_\eta = \mathbf{U}_\eta^\mathbf{T}\mathbf{U}_\eta$$

where, again, $\mathbf{U}_{\boldsymbol{\eta}}$ is an upper triangular matrix. In implementing this scheme, the matrix $\mathbf{R}_{\boldsymbol{\eta}}$ used is the estimate available at the start of the particular step of the recursion. Then a set of re-weighted GLS residuals, $\tilde{\tilde{\boldsymbol{\omega}}}$, can be calculated as

$$\tilde{\tilde{\boldsymbol{\omega}}} = \mathbf{U}_{\boldsymbol{\eta}}^{\mathbf{T}}\tilde{\boldsymbol{\omega}} = \mathbf{U}_{\boldsymbol{\eta}}^{\mathbf{T}}\mathbf{U}_{\mathbf{G}}^{-\mathbf{T}}\hat{\boldsymbol{\omega}} = \mathbf{U}_{\boldsymbol{\eta}}^{\mathbf{T}}\mathbf{U}_{\mathbf{G}}^{-\mathbf{T}}\left(\mathbf{y}-\hat{\mathbf{y}}\right).$$

The covariance matrix for the re-weighted GLS residuals is given by

$$\begin{aligned} E\left\{\tilde{\tilde{\boldsymbol{\omega}}}\tilde{\tilde{\boldsymbol{\omega}}}^{\mathbf{T}}\right\} &= E\left\{\mathbf{U}_{\boldsymbol{\eta}}^{\mathbf{T}}\mathbf{U}_{\mathbf{G}}^{-\mathbf{T}}\hat{\boldsymbol{\omega}}\hat{\boldsymbol{\omega}}^{\mathbf{T}}\mathbf{U}_{\mathbf{G}}^{-1}\mathbf{U}_{\boldsymbol{\eta}}\right\} = \mathbf{U}_{\boldsymbol{\eta}}^{\mathbf{T}}\mathbf{U}_{\mathbf{G}}^{-\mathbf{T}}\boldsymbol{\Sigma}_{\hat{\boldsymbol{\omega}}}\mathbf{U}_{\mathbf{G}}^{-1}\mathbf{U}_{\boldsymbol{\eta}}, \\ &= \sigma_{\eta}^{2}\left[\mathbf{R}_{\boldsymbol{\eta}} - \mathbf{U}_{\boldsymbol{\eta}}^{\mathbf{T}}\mathbf{U}_{\mathbf{G}}^{-\mathbf{T}}\mathbf{X}\left(\mathbf{X}^{\mathbf{T}}\mathbf{G}^{-1}\mathbf{X}\right)^{-1}\mathbf{X}^{\mathbf{T}}\mathbf{U}_{\mathbf{G}}^{-1}\mathbf{U}_{\boldsymbol{\eta}}\right]. \end{aligned}$$

Thus, the raw residual vector, $\hat{\boldsymbol{\omega}}$, has been rescaled to form a revised residual vector, $\tilde{\tilde{\boldsymbol{\omega}}}$, which, apart from the use of estimated values to form the re-weighting matrix (**G**), has a correlation matrix close to $\mathbf{R}_{\boldsymbol{\eta}}$.

Appendix D Details of weighting scheme

This appendix contains the background to the development of the weighting scheme used in the revised pooling procedure to calculate the pooled (weighted) L-moment ratios (L-CV and L-SKEW). While Section 6.4 contains a summary of the method, this appendix provides the background to the mathematical and statistical arguments and results.

For each catchment in the whole dataset (602 catchments in this study, and any new catchments for which estimates are required) a "local" model is used. These models are actually inconsistent between catchments, but the overall approach is used because it provides a way of defining a weighting scheme within a pooling-group which allows the weights to be varied according to some notion of catchment similarity. Each "local" model applies to a particular pooling-group centred on the subject or target catchment. Here the subject catchment is always treated as being included in the pooling-group for the mathematical analysis, whereas the data for the subject site would often not be available for real applications.

The aim is to find the parameters α, β to be used in a weighting scheme, where the weights are of the form

$$w_j^{(a)} \propto \left\{ \alpha + c_j^{(a)} + \beta D_j^{(a)} \right\}^{-1} \qquad j = 1, \cdots, P \ .$$

The following points of notation should be bourne in mind.

- The superscript (a) indicates a target catchment.
- The quantities $c_j^{(a)}$ are known constants, which are small or large according to whether the j'th catchment in the pooling-group has a long or a short data-record.
- The quantities $D_j^{(a)}$ are known constants which measure the distance (either in geographical space or in catchment-descriptor space) between the subject catchment "a" and the j'th catchment in the pooling-group, where the intention is to give low weights to those catchments at greatest distance.

Local models

For catchment a, identify the pooling-group of M members, where the subject catchment is always included and is identified in the mathematics by the subscript zero, while the others have subscripts $1, \ldots, P$. The local model corresponding to these weights (for a catchment a in the overall dataset) is

$$Y_j^{(a)} = \mu^{(a)} + \varepsilon_j^{(a)} + \eta_j^{(a)}, \qquad j = 0, \cdots, P \ ,$$

where $\mu^{(a)}$ is the local mean value for the pooling-group, $\varepsilon_j^{(a)}$ is the sampling error and $\eta_j^{(a)}$ is the modelling error. The errors $\varepsilon_j^{(a)}$ and $\eta_j^{(a)}$ here correspond to the idea that values for the catchments in the pooling-group will tend to centre around a common value $\mu^{(a)}$, but will differ from this because catchments in the pooling-group actually are different (each catchment will differ from $\mu^{(a)}$ by the modelling error $\eta_j^{(a)}$) and because only a limited record is available for each catchment (catchment values will have a sampling error $\varepsilon_j^{(a)}$ that would reduce in size as the record-length grows, but the values would centre around $T_j^{(a)} = \mu^{(a)} + \eta_j^{(a)}$).

The following assumptions are made for the two types of error:

$$\operatorname{var}\left(\varepsilon_j^{(a)}\right) = c_j^{(a)},$$

where $c_j^{(a)}$ are known sampling variances, depending on sample size); and

$$\operatorname{var}\left(\eta_j^{(a)}\right) = \alpha + \beta D_j^{(a)},$$

where $D_j^{(a)}$ is a measure of the distance between the subject catchment a and the j 'th catchment in the pooling-group. A way of using the dataset to establish a definition of this distance measure is outlined below. It is assumed that $D_0^{(a)} = 0$.

A further assumption is that that none of the catchments in a pooling-group will be close enough in geographical space for there to be correlation in either the modelling errors or the sampling errors.

According to this model, for a site j in the pooling-group $(j \neq 0)$,

$$\begin{aligned} \mathrm{E}\left\{\left(Y_0^{(a)} - Y_j^{(a)}\right)^2\right\} &= \mathrm{E}\left\{\left(\varepsilon_0^{(a)} + \eta_0^{(a)} - \varepsilon_j^{(a)} - \eta_j^{(a)}\right)^2\right\} \\ &= c_0^{(a)} + c_j^{(a)} + \left(\alpha + \beta d_0^{(a)}\right) + \left(\alpha + \beta d_j^{(a)}\right), \\ &= c_0^{(a)} + c_j^{(a)} + 2\alpha + \beta d_j^{(a)}. \end{aligned} \qquad \text{(D.1)}$$

Thus, if the adjusted pairwise contributions to a variogram analysis are defined as

$$\hat{v}_j^{(a)} = \left(Y_0^{(a)} - Y_j^{(a)}\right)^2 - \left(c_0^{(a)} + c_j^{(a)}\right) \qquad j = 1, \cdots, P; \quad a = 1, \cdots, N, \qquad \text{(D.2)}$$

when plotted against the distance $D_j^{(a)}$, these should cluster around the line defined by $\hat{v}_j^{(a)} = 2\alpha + \beta D_j^{(a)}$ as seen by comparing equations (D.1) and (D.2). In practice, this approach is modified to plot averages of the $v_j^{(a)}$ within distance-based cells, against distance. This gives a way of finding a good choice for the distance measure D, given that candidate measures are the geographical distance and the “similarity distance measure”, *SDM,* described in Chapter 6. Specifically, plots can be constructed of $\hat{v}_j^{(a)}$ against these distances with the intention of choosing the best relationship and of choosing a functional form for the relationship. This procedure is described in Chapter 6 : this outlines a more general version of the above, in which an allowance is made for the correlation between the sampling errors.

Assuming that the distances and the parameters α and β can be identified, it is convenient to introduce the following notation for quantities now regarded as known:

$$\operatorname{var}\left(\eta_j^{(a)}\right) = \alpha + \beta D_j^{(a)} = b_j^{(a)}.$$

If the local model is assumed to hold for the given subject site, then the optimal weights can be found for two different cases:

- no information for the subject site (an ungauged catchment);
- limited information for the subject site (a gauged catchment).

In each case the quantity that is to be estimated for catchment “a” is

$$T^{(a)} = T_0^{(a)} = \mu^{(a)} + \eta_0^{(a)}.$$

Note that the “true” value $T^{(a)}$ for the subject site includes the term $\eta_0^{(a)}$ for the modelling error for the reason outlined above. Note also that the local model only leads to a simple weighting scheme of the type sought here if the assumption of uncorrelated errors (both modelling errors and sampling errors) is temporarily adopted. It has already been remarked that the local models taken across catchments are inconsistent with one another, and the models are somewhat deficient in not allowing for correlation in the errors. However, the only use being made of these models is to suggest a structure for how the weights within a pooling-group might usefully be constructed: these weighting schemes are tested and compared in a way which does not rely on these local models.

Case 1 - No information for the subject site (ungauged catchment)

The estimate for the target catchment is defined as

$$\hat{T}^{(a)} = \sum_{j=1}^{P} w_j^{(a)} Y_j^{(a)}$$

for a set of weights $\left\{w_j^{(a)}; j = 1, \cdots, P\right\}$ which sum up to one. The error in the estimate is, according to the local model,

$$\begin{aligned} e^{(a)} &= T^{(a)} - \hat{T}^{(a)}, \\ &= \mu^{(a)} + \eta_0^{(a)} - \sum_{j=1}^{P} w_j^{(a)} \left\{\mu^{(a)} + \varepsilon_j^{(a)} + \eta_j^{(a)}\right\}, \\ &= \eta_0^{(a)} - \sum_{j=1}^{P} w_j^{(a)} \left\{\varepsilon_j^{(a)} + \eta_j^{(a)}\right\}, \end{aligned}$$

and the expected squared error is

$$E\left\{\left(e^{(a)}\right)^2\right\} = b_0^{(a)} + \sum_{j=1}^{P} \left(w_j^{(a)}\right)^2 \left\{c_j^{(a)} + b_j^{(a)}\right\}.$$

The expected squared error is minimised, over choices of sets of weights which sum to one, by setting

$$w_j^{(a)} = \frac{\left\{c_j^{(a)} + b_j^{(a)}\right\}^{-1}}{\sum_{k=1}^{P} \left\{c_k^{(a)} + b_k^{(a)}\right\}^{-1}}.$$

This choice gives

$$E\left\{\left(e^{(a)}\right)^2\right\} = b_0^{(a)} + \frac{1}{\sum_{k=1}^{P} \left\{c_k^{(a)} + b_k^{(a)}\right\}^{-1}}.$$

Case 2 - Data available at the subject site (gauged catchment)

This is the case where a pooling-group is formed for a catchment with gauged data, where the sample information is in the form of an observed value $Y_0^{(a)}$ which has a sampling error variance of $c_0^{(a)}$. The estimate is defined as

$$\hat{T}^{(a)} = \sum_{j=0}^{P} w_j^{(a)} Y_j^{(a)}$$

for a set of weights $\left\{ w_j^{(a)}; j = 0, \cdots, P \right\}$ which sum up to one. The error in the estimate is, according to the local model,

$$\begin{aligned} e^{(a)} &= T^{(a)} - \hat{T}^{(a)}, \\ &= \mu^{(a)} + \eta_0^{(a)} - \sum_{j=0}^{P} w_j^{(a)} \left\{ \mu^{(a)} + \varepsilon_j^{(a)} + \eta_j^{(a)} \right\}, \\ &= \left\{ 1 - w_0^{(a)} \right\} \eta_0^{(a)} - w_0^{(a)} \varepsilon_0^{(a)} - \sum_{j=1}^{P} w_j^{(a)} \left\{ \varepsilon_j^{(a)} + \eta_j^{(a)} \right\}, \end{aligned}$$

and the expected squared error is

$$E\left\{ \left(e^{(a)} \right)^2 \right\} = \left\{ 1 - w_0^{(a)} \right\}^2 b_0^{(a)} + \left(w_0^{(a)} \right)^2 c_0^{(a)} + \sum_{j=1}^{P} \left(w_j^{(a)} \right)^2 \left\{ c_j^{(a)} + b_j^{(a)} \right\}.$$

This is minimised over choices of weights summing to one by

$$w_0^{(a)} = \frac{b_0^{(a)}}{c_0^{(a)} + b_0^{(a)}} + \frac{c_0^{(a)} \left\{ c_0^{(a)} + b_0^{(a)} \right\}^{-2}}{\sum_{k=0}^{P} \left\{ c_k^{(a)} + b_k^{(a)} \right\}^{-1}}, \qquad j = 0,$$

$$w_j^{(a)} = \frac{c_0^{(a)} \left\{ c_0^{(a)} + b_0^{(a)} \right\}^{-1} \left\{ c_j^{(a)} + b_j^{(a)} \right\}^{-1}}{\sum_{k=0}^{P} \left\{ c_k^{(a)} + b_k^{(a)} \right\}^{-1}}, \qquad j = 1, \cdots, P.$$

If the set of weights that would be obtained with the observation for catchment “a” not treated in a special way are defined by

$$u_j^{(a)} = \frac{\left\{ c_j^{(a)} + b_j^{(a)} \right\}^{-1}}{\sum_{k=0}^{P} \left\{ c_k^{(a)} + b_k^{(a)} \right\}^{-1}} \qquad j = 0, \cdots, P,$$

it follows that

$$\begin{aligned} w_0^{(a)} &= \frac{b_0^{(a)}}{c_0^{(a)} + b_0^{(a)}} + \frac{c_0^{(a)}}{c_0^{(a)} + b_0^{(a)}} u_0^{(a)}, \\ w_j^{(a)} &= \frac{c_0^{(a)}}{c_0^{(a)} + b_0^{(a)}} u_j^{(a)}, \qquad j = 1, \cdots, P. \end{aligned}$$

The estimator which does not treat the subject site as a special case with the pooling-group can be defined (as in Case 1) as

$$\hat{T}^{(a)*} = \sum_{j=0}^{P} u_j^{(a)} Y_j^{(a)},$$

and it then follows that the estimator for the gauged-catchment case can be written as

$$\hat{T}^{(a)} = \sum_{j=0}^{P} w_j^{(a)} Y_j^{(a)} = \frac{b_0^{(a)}}{c_0^{(a)} + b_0^{(a)}} Y_0^{(a)} + \frac{c_0^{(a)}}{c_0^{(a)} + b_0^{(a)}} \hat{T}^{(a)*},$$

$$= \frac{b_0^{(a)}}{c_0^{(a)} + b_0^{(a)}} \left\{ Y_0^{(a)} - \hat{T}^{(a)*} \right\} + \hat{T}^{(a)*}.$$

Glossary

AMAX	Data which are “annual maxima” – a data series consisting of the largest value occurring in each year. For flood data the year concerned is the “hydrological year”, defined as running from 1 October to 30 September of the next year.
AREA	One of the catchment descriptor variables derived for the FEH study and used in this project. It represents the area of the catchment upstream of the given gauge location, using the catchment derived from a digital terrain model.
BFIHOST	One of the catchment descriptor variables used for the FEH study and also used in this project. It consists of an estimate of the BaseFlow Index (BFI) derived from a spatial dataset of land-uses. The BFI measure quantifies the proportion of the overall flow from a catchment that is attributed to slow-response pathways.
DDF	An abbreviation for Depth-Duration-Frequency. A DDF model was used in the FEH procedures to estimate the amount of rainfall (Depth) that might occur over a given time interval (Duration) at a given rarity (Frequency).
DTM	An abbreviation for Digital Terrain Model. The DTM used in this study is a particular computer database founded on flow pathways.
EVAP	One of the new catchment descriptor variables derived for this project. It is the catchment average value of the annual average total potential evaporation.
FARL	One of the catchment descriptor variables derived for the FEH study and used in this project. It is an attempt to quantify the overall effect that on-line reservoirs and lakes in a catchment would have in reducing flood peaks at the catchment outlet.
FEH	A short name for the Flood Estimation Handbook (Institute of Hydrology, 1999).
FPDBAR	One of the new catchment descriptor variables derived for this project. It quantifies the average flood depth upstream of the catchment outlet for a rare flood which is defined in a consistent way across all catchments.
Flood Frequency Curve	The flood frequency curve for a river location relates the size of a flood (measured in term of flow) to the rarity of the flood. Often flood frequency curves relate the annual maximum flow to the return period.
FPEXT	One of the new catchment descriptor variables derived for this project. It quantifies the relative spatial extent compared to the catchment size for the area that would be flooded in rare floods defined in a consistent way across all catchments.
FPLOC	One of the new catchment descriptor variables derived for this project. It quantifies the location within a catchment the area that would be flooded in a rare flood, where this is defined in a consistent way across all catchments.
FSR	A short name for the Flood Studies Report (NERC, 1975).

fse	Factorial Standard Error. A measure of the average size of errors in a set of estimates, where errors are measured as proportions of the values in contrast to ordinary standard errors where the error is a difference.
GEV	Generalised Extreme Value distribution – a particular family of statistical distributions.
GLO	Generalised Logistic distribution – a particular family of statistical distributions.
GLS	Generalised Least Squares – a model-fitting formulation which is an extension of both OLS and WLS and which fits a linear regression model in an optimal manner, taking into account the correlation (an aspect of statistical dependence) between the errors associated with different observations.
Growth curve	The growth curve for a catchment represents a re-scaling of the flood frequency curve using the index flood for the catchment, where the effect of the rescaling is to reduce the differences between different catchments. Once scaled by the index floods, growth curves allow one to assess whether floods on different catchments grow more or less quickly as a function of return period.
Index flood	The index flood is an important component of the index-flood approach to analysing flooding across a set of catchments. It is a measure of the typical size of the annual maximum flood on a catchment. The basis of the index-flood approach is that dividing the values in the series of annual maximum by the index flood reduces differences in the statistical properties between catchments, or at least makes these easier to handle. The present study uses the median annual maximum (QMED) as the index flood.
Nugget effect	A term used in connection with variograms. A variogram contains a nugget effect if it does not approach zero as the distance approaches zero. It corresponds to cases where the spatial field being considered does not vary smoothly and where values at each location can be affected by purely local variations that do not affect immediately adjacent locations. The term derives from mining applications, where a spread of one mineral may contain nuggets of another.
OLS	Ordinary Least Squares – the fitted model or the calculation procedure for a linear regression model in which the parameters are fitted by minimising an unweighted sum of squares of the errors (observed value minus modelled value). The procedure is optimal under restrictive conditions, but will usually give reasonably good results.
POT	Data or an approach to data analysis which keeps track of the highest flow during each event, where “events” are defined as time-periods where the flow exceeds a given value or threshold – “Peaks Over Threshold”. In data extraction, rules are applied to establish whether peaks occurring close together should be counted as separate events.
PRAT	One of the new catchment descriptor variables derived for this project. It quantifies the steepness of the rainfall-frequency curve for the catchment average rainfall.

PUM	Pooled Uncertainty Measure. This measure is used to assess the accuracy of estimates of the growth curve obtained by using pooling-groups and, in particular, it is used to compare different variants of the method. It compares pooled estimates treating a catchment as ungauged, with at-site estimates obtained from the gauged record.
QBAR	The average annual maximum flow – this may be the average of the annual maximum in a data-record, or the notional value that would be obtained from a very long series of data under stable climate conditions.
QMED	The median annual maximum flow – this may be either the median derived from the available data (sample median), or the notional value that would be obtained from a very long series of data under stable climate conditions. The median is a number such that half the values in a series are below that number and half above. For floods, half of the years in a dataset would contain one or more floods, for which the flow is greater than QMED.
Q_{100}	The flow having a 100-year return period or, equivalently, the value of flow that has a 1 per cent chance of being exceeded in any one year.
ROI	The Region-Of-Influence (ROI) approach defines for each subject location a set of catchments that are hydrologically similar based on similarity of catchment descriptors. These sets of catchments will vary as the subject location shifts. This contrasts with earlier methodology in which a small set of fixed regions was used.
SAAR	One of the catchment descriptor variables used for the FEH study and also used in this project. It represents a catchment average value for the annual average total rainfall for a standard period (1961-1990).
SDM	The "similarity distance measure" which quantifies the similarity between catchments based on their catchment descriptors. This is the measure used to assess hydrological similarity.
URBEXT	One of the catchment descriptor variables used for the FEH study and also used in this project. It is used to identify whether a catchment is judged to be "rural" and so can be included in a set of catchments thought not to be markedly affected by urbanisation. It measures the fraction of the catchment flagged as "urban" or "suburban" in the underlying data-sets.
URBLOC	One of the catchment descriptor variables developed for the FEH study. It is not used in this project, but is cited as an analogue when discussing FPLOC. It measures the location relative to the catchment outlet of locations flagged as "urban" or "suburban" in the underlying data-sets.
WLS	Weighted Least Squares – the fitted model or the calculation procedure for a linear regression model in which the parameters are fitted by minimising a weighted sum of squares of the errors (observed value minus modelled value): here the weights affect how much importance is attributed to a given observation. See also GLS and OLS.

List of Symbols

b_i	Model parameter describing the weight assigned to catchment i in a pooling group.
β	Scale parameter of the GLO distribution.
c_i	Model parameter describing the weight assigned to catchment i in a pooling group.
d_{ij}	Distance between catchment centroids for catchments i and j.
ε_i	Sample error at catchment i.
$\gamma(s)$	Variogram for distance s, where s is a value of the "similarity distance measure" (*SDM*).
$\mathbf{G}$	Normalised total regression error covariance. Introduced for computational convenience.
κ	Shape parameter of the GLO distribution.
η_i	Model error at catchment i.
n_i	Sample size (record length) at catchment i.
n_{ij}	Number of overlapping years between records at catchments i and j.
ξ	Location parameter of the GLO distribution.
$r_{\varepsilon,d}$	Sample error correlation between catchments which are a distance d apart.
$r_{\varepsilon,ij}$	Sample error correlation between catchments i and j.
$r_{\eta,d}$	Model error correlation between catchments which are a distance d apart.
$r_{\eta,ij}$	Model error correlation between catchments i and j.
$\mathbf{R}_\eta$	Regression model error correlation matrix.
$\mathbf{\Sigma}_\varepsilon$	Sampling error covariance matrix.
$\mathbf{\Sigma}_\eta$	Model error covariance matrix.
$\mathbf{\Sigma}_\varpi$	Covariance matrix of the total regression error (sampling error plus modelling error).
s	Short notation for the similarity distance measure (*SDM*).
σ^2	Sampling variance of the log-transformed median annual maximum peak flow.
σ_η^2	Variance of the regression model error for lnQMED.
σ_γ^2	Variance of the regression model error for $\ln\beta$.
$\boldsymbol{\theta}$	Vector of parameters in the regression model for lnQMED..
τ_r	Population value of the L-moment ratio of order r.
t_r	Sample value of the L-moment ratio of order r.
ϕ	Model parameters describing the correlation of the sampling errors of log-transformed median annual maximum flood.
φ	Model parameters describing the correlation between the regression model errors.

$\mathbf{x}_i$	Vector of catchment descriptors for catchment i.
$\mathbf{X}$	Matrix of catchment descriptor values for all catchments used to estimate the regression model.
y_i	Observed value of log-transformed median annual maximum peak flow
$\mathbf{y}$	Vector of observed values in the regression model, containing elements y_i.
y_T	Reduced Gumbel variate at return period T.
ω_i	Weight given to the catchment ranked as number i in a pooling group.
w_i	Weight given to catchment i when estimating the pooled uncertainty measure (PUM).
z_T	Growth factor for return period T as derived from a GLO distribution.

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