Estimating flood peaks and hydrographs for small catchments:

R5 – Pooling-group formation for small catchments

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Executive summary

The existing FEH statistical method uses ‘pooling-groups’ to estimate flood frequency relationships in ungauged catchments and to extend the amount of data available for flood peak estimations in gauged catchments, reducing uncertainty in the magnitudes of long return period floods. The current method for selecting pooling-groups is heavily weighted towards catchment area, meaning that pooling-groups for small catchments tend to be populated with other small catchments, due to the limited number of gauged small catchments in the UK that are suitable for including in pooling-groups. As a result, the derived magnitude-return period relationships for small catchments tend not to vary as much as for larger catchments, despite the wide range of small catchment types.

This study analyses a data set of gauged 191 small catchments, in order to determine if there are important factors, other than area, influencing the relationships between rarer and more common floods in small catchments, and to identify the relative importance of those other factors.

Based on performance metrics used in the Flood Estimation Handbook and the comprehensive 2008 update to the FEH statistical method, it is found that catchment area is an important differentiator of flood growth curves in small catchments. However, SAAR (catchment average annual rainfall) is found to be equally important. A new similarity distance measure for selecting pooling-groups for small catchments is proposed in Equation 12, in Section 5.2 of this report. This is found to offer slightly lower pooled uncertainty and to create more homogeneous pooling-groups than the measure used in developing the existing FEH statistical method. However, unlike the existing measure, the new measure is not found to select similar groups for a range of small catchments.

Important Note:

Work on Project SC090031 ‘Estimating flood peaks and hydrographs in small catchments (Phase 2)’ began in December 2013. Tasks carried out in the early stages of the project have already been documented in several project notes and reports, so it is possible that there may be inconsistencies, particularly in the various data sets and methods that have been applied at different points in time. This report provides a summary of the research carried out throughout the project, and we have detailed the data sets and methods used in each of the stages and tasks.

1. Introduction

In the existing FEH statistical method (Kjeldsen and others, 2008), a flexible regionalisation method based on Burn (1990) is used for estimating long return period flood peaks at ungauged sites, and for reducing uncertainty at gauged sites, particularly where the gauged record is short compared to the return period to be estimated. The flexible regions are known as 'pooling-groups' and are populated by the gauged catchments most similar to the catchment of interest in terms of a similarity distance measure (SDM), which is based on a combination of catchment descriptors found to influence the distributions of annual maximum (AMAX) flows.

In order to use the pooling-group method, recorded AMAX at several catchments most 'similar' to the one of interest are standardised, the second and third L-moments (L-CV and L-SKEW) of the AMAX series are calculated individually for each catchment, and weighted averages of those L-moments define the pooled L-moments for the catchment of interest. If the catchment of interest is gauged, it can be included in the pooling-group, with an enhanced weight applied to its own AMAX series, to define the enhanced single-site L-moments. The pooled (for ungauged catchments) or enhanced single-site (for gauged catchments) L-moments are used to parameterise an appropriate flood frequency distribution, usually the generalised logistic (GLO), which is used to estimate the magnitude of the flood peak of interest. As every catchment is different, every pooling-group is different, either in terms of its members or in terms of each member's weight. The existing FEH statistical method defines similarity in terms of the difference between the catchment of interest and each potential pooling-group member in four FEH catchment descriptors: AREA, SAAR, FARL and FPEXT. AREA is given the heaviest weight by far in this SDM, which has led to criticism from some users of the existing FEH statistical method that there is little variation in the pooling-groups generated for small catchments in general. This occurs because there are few small catchments rated with sufficient gauging quality for pooling. It is also plausible, though by no means proven, that different runoff generation processes in small catchments may mean having to use different catchment descriptors to define similarity.

In this study, the SDM is revisited specifically for small catchments. Catchment descriptors explaining variation in L-CV and L-SKEW in catchments up to 25 km^2 are identified and then tested as the basis for new SDMs. Other aspects of the pooling method (for example, weighting of pooling-group members, 500-year target pooling-group length) are maintained, so that new potential SDMs for small catchments are compatible with all other parts of the existing method. Four new catchment descriptors, two defining catchment elongation and two defining orientation in north-south and east-west components, are created and evaluated against L-moments for potential use in a new SDM.

It is assumed that the reader has a detailed understanding of FEH methods, hydrological terminology, and catchment descriptors.

2. Study data

2.1 ‘Target’ small catchments

A total of 191 small catchments are available for this study. These are a subset of the 217 initially identified for the ‘Small catchments’ project, excluding 25 catchments for which AMAX series are not available, and Hebden Beck at Hebden (NRFA No. 27032), where dye tracing has shown that water entering Mossdale Caverns, inside the topographical catchment, drains out of the topographical catchment (Faulkner, pers. comm.).

Table 1 subdivides the 191 small catchments studied here into groups according to catchment area and assessment of data quality by the measuring authorities (QMED/pooling suitability). The group ‘Other’ includes catchments assessed as suitable for neither pooling nor QMED, and catchments that the measuring authorities have not assessed.

Table 1 - Small catchment size and data quality groups

Data quality	0 to 25 km^2	25 to 40.9 km^2	TOTAL
Suitable for pooling and QMED	28	29	57
Suitable for QMED only	65	30	95
Other	39	0	39
TOTAL	132	59	191

57 catchments are assessed as suitable for pooling, 28 of which are less than 25 km^2. As AREA is the main criterion for selecting pooling-groups, it is implied that many small catchment pooling-groups would be populated mainly or entirely by these catchments in a default pooling analysis, quantitatively confirming the perception that there is little variation in small catchment pooling-groups.

The following pages (Figures 1-6) plot L-moments against catchment descriptors (including four new descriptors defined in Section 2.3) in order to assess if useful information can also be derived from catchments not meeting these strict criteria. These are defined as follows:

- AREA, km^2: catchment area on the Integrated Hydrological Digital Terrain Model (IHDTM). For the 4 catchments under 0.5 km^2, including 2 with IHDTM area over 0.5 km^2, nominal areas are used instead. In practice, it is very important that practitioners check the accuracy of the IHDTM area using local information - see page 149 of the Flood Estimation Guidelines (LIT 11832: Environment Agency, 2022) for further details

- BFIHOST: baseflow index estimated from HOST soil data
- FARL: flood attenuation due to reservoirs and lakes - dependent on the fraction of catchment covered by on-line water bodies and their proximity to the catchment outlet
- FPEXT: Fraction of catchment with greater-than-zero 100-year flood depth
- SAAR, mm: mean annual rainfall depth recorded in catchment from 1961 to 1990
- $URBEXT_{2000}$: Weighted fraction of catchment assigned as urban, suburban or inland bare ground. See Bayliss and others (2006) for details of calculation
- DPLBAR, km: Mean drainage path length on the IHDTM
- DPSBAR, m/km: Mean drainage path slope on the IHDTM
- PROPWET: proportion of period from January 1961 to December 1990 when soil moisture deficit estimated via MORECS is less than 6 mm
- ALTBAR, m: Mean altitude of catchment above sea level, as defined on IHDTM
- ASPBAR, degrees: Mean orientation of catchment, clockwise from north
- ASPVAR: Variability in orientation of catchment slope
- LDP, km: Longest drainage path on the IHDTM
- SPRHOST: standard percentage runoff estimated from HOST soil data
- FPDBAR, cm: Mean depth of 100-year flood over entire catchment. The non-flooded proportion of the catchment is included in the calculation with a flood depth of zero
- FPLOC: Mean distance of 100-year flood plain from catchment outlet, standardised by DPLBAR
- RMED13-1H, mm: 1-hour, 2-year rainfall depth from FEH13 rainfall model
- RMED13-6H, mm: 6-hour, 2-year rainfall depth, from FEH13 rainfall model
- RMED13-1D, mm: 24-hour, 2-year rainfall depth, from FEH13 rainfall model
- RMED13-2D, mm: 48-hour, 2-year rainfall depth, from FEH13 rainfall model
- LONG, SHAPE, $ALIGN_V$ and $ALIGN_H$ are defined in section 2.3 of this report

Due to space constraints on the plots, the legend for all of Figures 1-6 is produced below:

● Pooling, < 25 km^2
○ QMED, < 25 km^2
○ Other, < 25 km^2
△ Pooling, 25-40.9 km^2
△ QMED, 25-40.9 km^2

The legend shows: Pooling <25 km^2 (filled purple dots), QMED <25 km^2 (yellow circles), Other <25 km^2 (green circles), Pooling, 25-40.9 km^2 (purple triangles), QMED, 25-40.9 km^2 (yellow triangles).

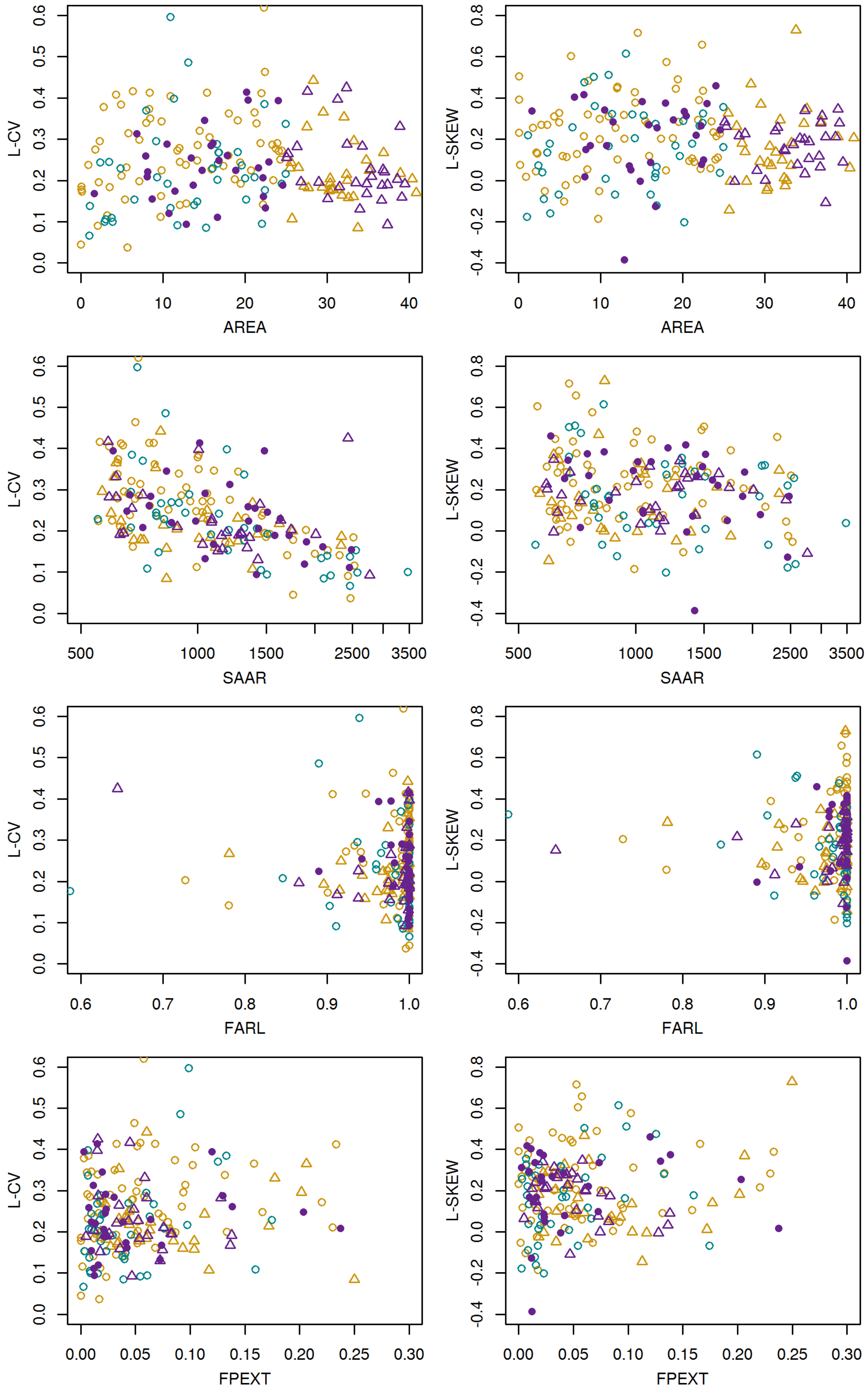

Figure 1 - L-moments vs. catchment descriptors (AREA, SAAR, FARL, FPEXT)

The scatter graphs in Figure 1 plot L-moments (L-CV and L-SKEW) against four catchment descriptors:

- AREA, km^2: catchment area on the Integrated Hydrological Digital Terrain Model (IHDTM) - for the four catchments under 0.5 km^2, including two with IHDTM area over 0.5 km^2, nominal areas are used instead
- SAAR, mm: mean annual rainfall depth recorded in catchment from 1961 to 1990.
- FARL: flood attenuation due to reservoirs and lakes - dependent on the fraction of catchment covered by on-line water bodies and their proximity to the catchment outlet
- FPEXT: Fraction of catchment with greater-than-zero 100-year flood depth

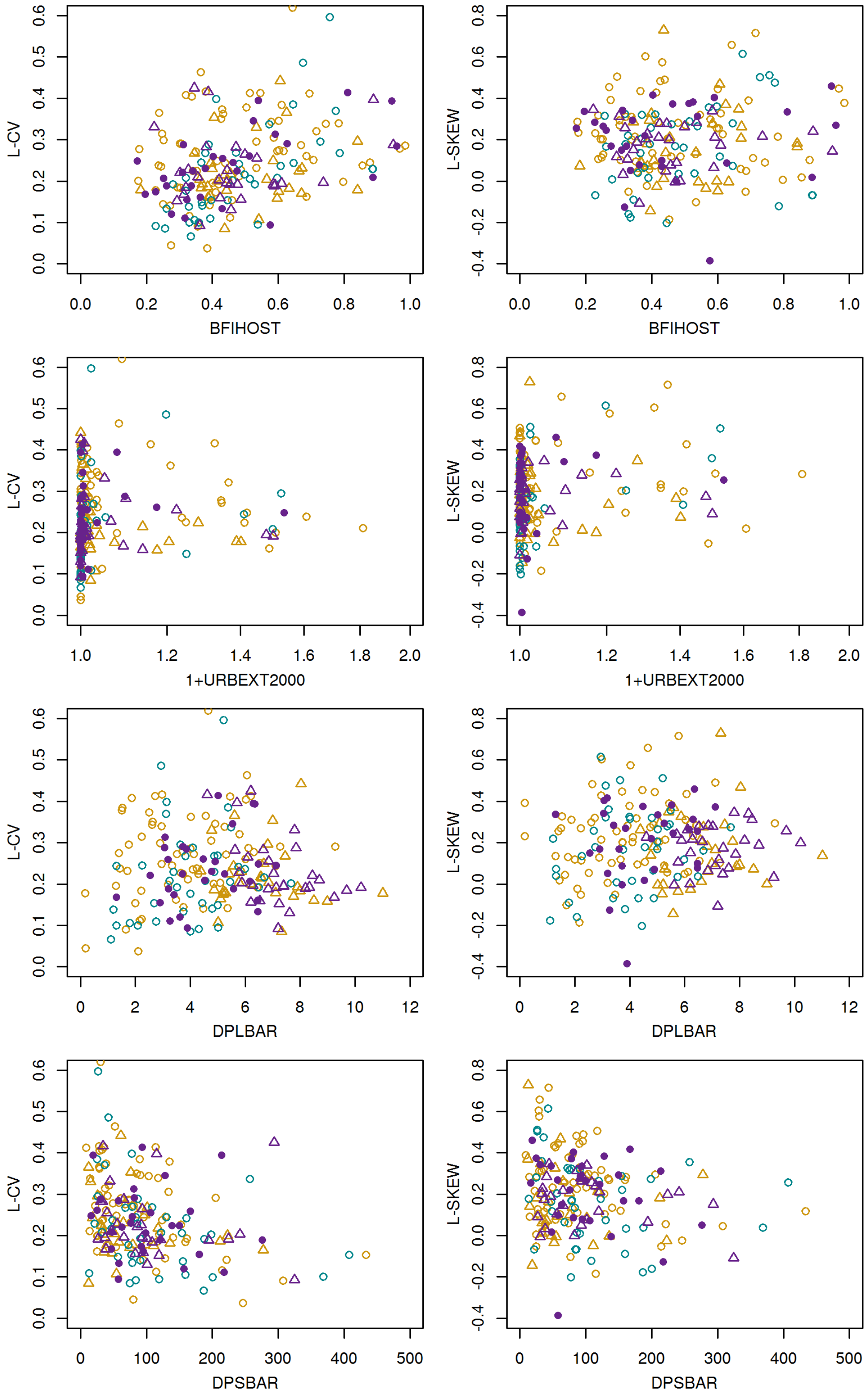

Figure 2 - L-moments vs. catchment descriptors (BFIHOST, URBEXT$_{2000}$, DPLBAR, DPSBAR)

The scatter graphs in Figure 2 plot L-moments (L-CV and L-SKEW) against four catchment descriptors:

- BFIHOST: baseflow index estimated from HOST soil data

- $URBEXT_{2000}$: weighted fraction of catchment assigned as urban, suburban or inland bare ground - see Bayliss and others (2006) for details of calculation
- DPLBAR, km: mean drainage path length on the IHDTM
- DPSBAR, m/km: mean drainage path slope on the IHDTM

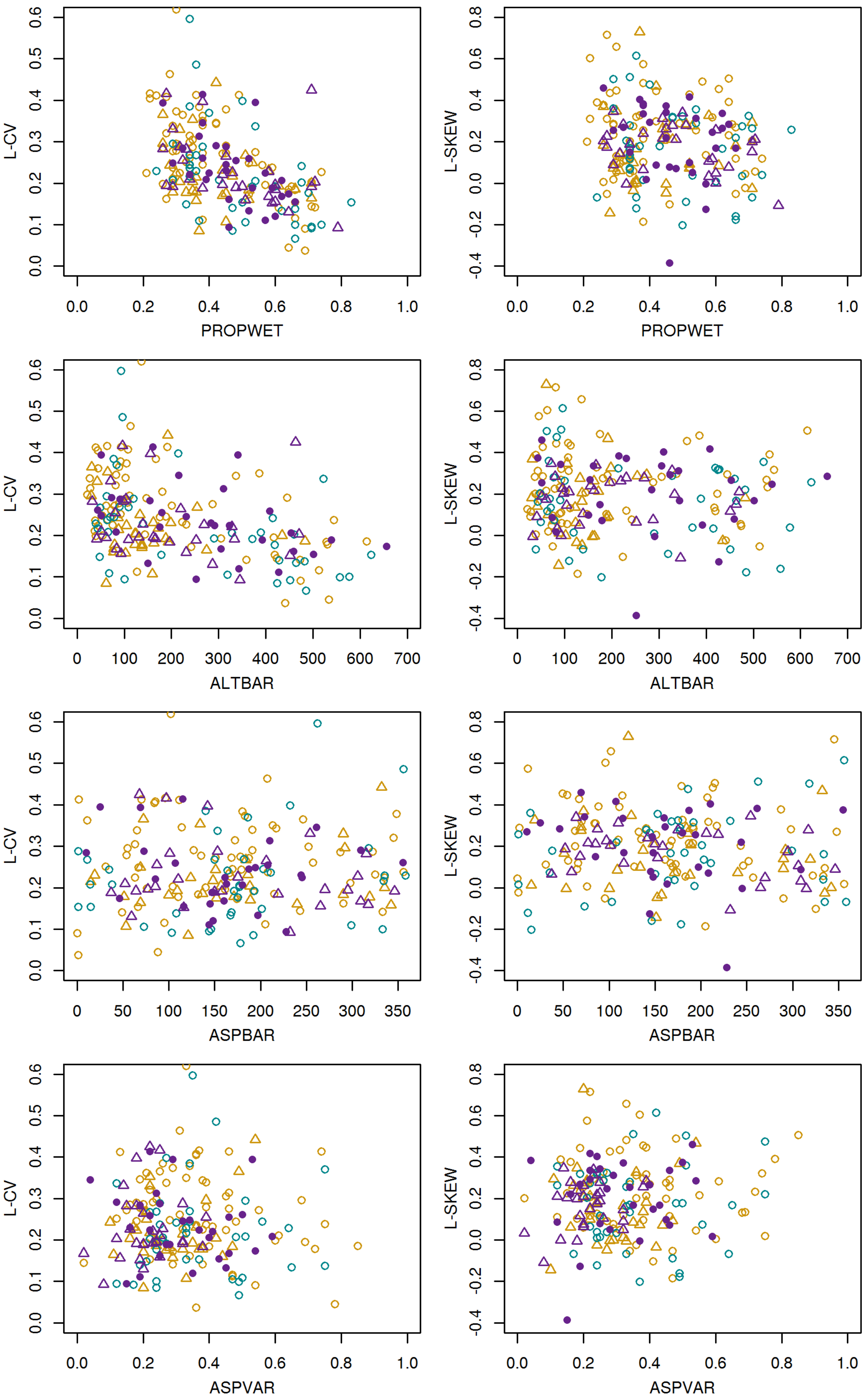

Figure 3 - L-moments vs. catchment descriptors (PROPWET, ALTBAR, ASPBAR, ASPVAR)

The scatter graphs in Figure 3 plot L-moments (L-CV and L-SKEW) against four catchment descriptors:

- PROPWET: proportion of period from January 1961 to December 1990 when soil moisture deficit estimated via MORECS is less than 6 mm
- ALTBAR, m: mean altitude of catchment above sea level, as defined on IHDTM
- ASPBAR, degrees: mean orientation of catchment, clockwise from north
- ASPVAR: variability in orientation of catchment slope

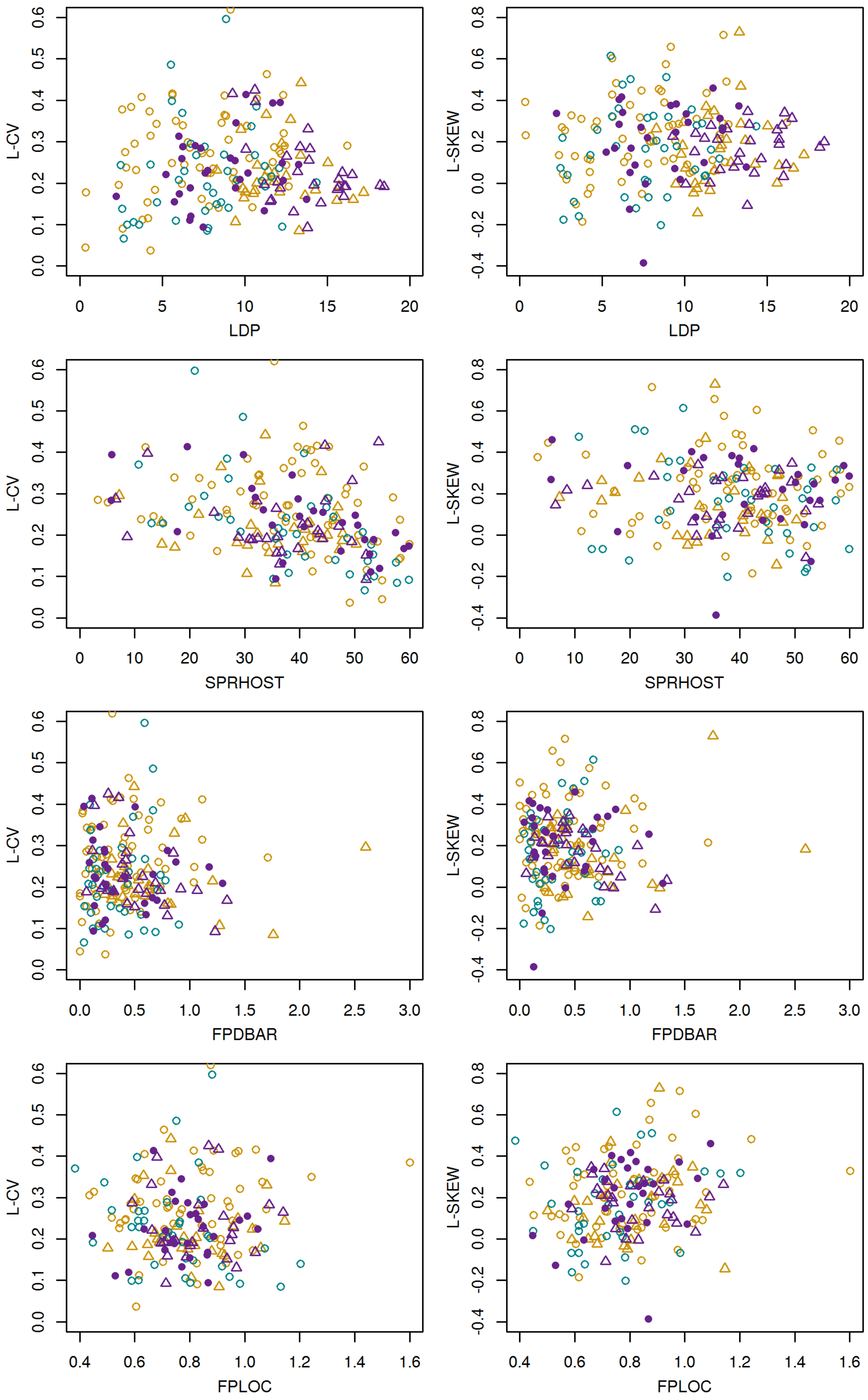

Figure 4 - L-moments vs. catchment descriptors (LDP, SPRHOST, FPDBAR, FPLOC)

The scatter graphs in Figure 4 plot L-moments (L-CV and L-SKEW) against four catchment descriptors:

- LDP, km: longest drainage path on the IHDTM
- SPRHOST: standard percentage runoff estimated from HOST soil data
- FPDBAR, cm: mean depth of 100-year flood over entire catchment - the non-flooded proportion of the catchment is included in the calculation with a flood depth of zero
- FPLOC: mean distance of 100-year flood plain from catchment outlet, standardised by DPLBAR

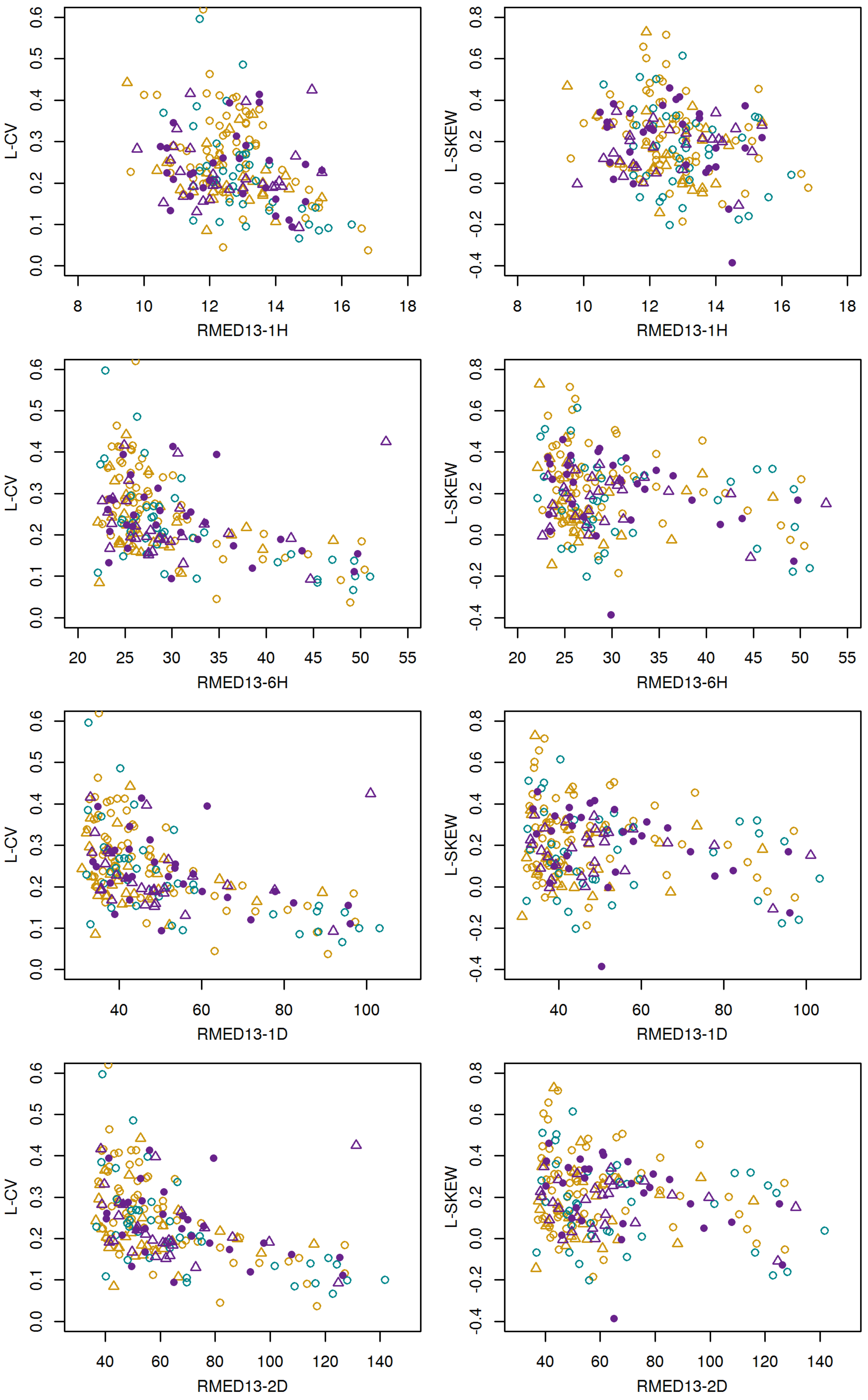

Figure 5 - L-moments vs. catchment descriptors (RMED 13-1H, RMED 13-6H, RMED 13-1D, RMED 13-2D)

The scatter graphs in Figure 5 plot L-moments (L-CV and L-SKEW) against four catchment descriptors:

- RMED13-1H, mm: 1-hour, 2-year rainfall depth from FEH13 rainfall model
- RMED13-6H, mm: 6-hour, 2-year rainfall depth, from FEH13 rainfall model
- RMED13-1D, mm: 24-hour, 2-year rainfall depth, from FEH13 rainfall model
- RMED13-2D, mm: 48-hour, 2-year rainfall depth, from FEH13 rainfall model

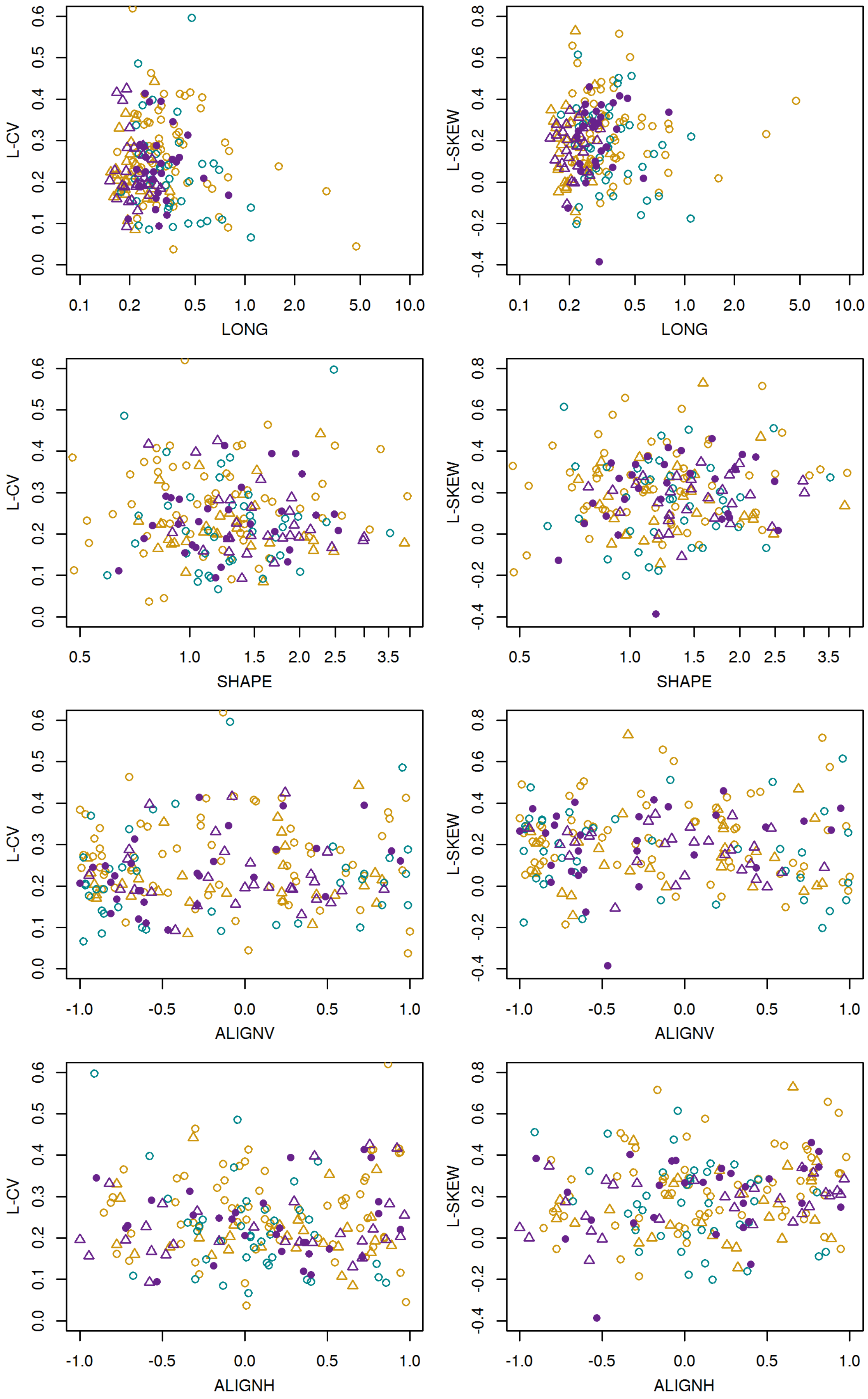

Figure 6 - L-moments vs. catchment descriptors (LONG, SHAPE, ALIGN$_V$, ALIGN$_H$)

The scatter graphs in Figure 6 plot L-moments (L-CV and L-SKEW) against four catchment descriptors:

- $ALIGN_V$: a measure of how strongly a catchment is oriented north-south - strong north orientations result in values near +1 and strong south orientations result in values near −1
- $ALIGN_H$: a measure of how strongly a catchment is oriented east-west - strong east orientations result in values near +1 and strong west orientations result in values near −1
- LONG: a measure of the shape or elongation of the catchment
- SHAPE: a dimensionless measure equivalent to LONG

Figures 1 to 6 do not show many obvious relationships between catchment descriptors and L-moments. The strongest relationships seem to be between L-CV and either SAAR, RMED13 descriptors or PROPWET. Other, weaker relationships can be observed between L-CV and either BFIHOST, SPRHOST or DPSBAR. Different groups of catchments, based on size and suitability, show similar relationships. There are no obvious relationships between L-SKEW and any catchment descriptor. These findings are broadly consistent with previous regression studies on larger data sets, including catchments up to ~10,000 km^2 (Robson and Reed 1999, Kjeldsen and others, 2008), which found that little variation in either L-CV or L-SKEW could be explained directly through catchment descriptors.

2.2 Potential pooling-group members

The National River Flow Archive (NRFA) holds a database of around 1,000 UK gauging stations, with associated AMAX and peaks-over-threshold series. Data quality is assessed for every station in this database, and, in a standard pooling-group analysis, only rural catchments marked as suitable for pooling can be included in a pooling-group. Here, the same criteria will be used for selecting pooling-groups, using version 4.1 of the NRFA database, allowing 397 catchments in Great Britain and 27 catchments in Northern Ireland, ranging from 1.63 to 4,587 km^2 in area, to be selected.

2.3 New catchment descriptors

Four new catchment descriptors were proposed and generated for this study:

1. $ALIGN_V$: A measure of how strongly a catchment is oriented north-south. Strong north orientations result in values near +1 and strong south orientations result in values near −1 (Equation 1):

Equation 1 - $\mathrm{ALIGN_V}$ catchment descriptor

$$ALIGN_v = 2\left|\frac{ASPBAR - 180}{180}\right| - 1$$

2. $\mathrm{ALIGN_H}$: A measure of how strongly a catchment is oriented east-west. Strong east orientations result in values near +1 and strong west orientations result in values near −1 (Equation 2):

Equation 2 - ALIGN_{H} catchment descriptor

$$ALIGN_H = \begin{cases} 2\left|\frac{ASPBAR + 90}{180}\right| - 1 & 0 \le ASPBAR < 90 \\ 2\left|\frac{ASPBAR - 270}{180}\right| - 1 & 90 \le ASPBAR < 360 \end{cases}$$

$\mathrm{ALIGN_H}$ and $\mathrm{ALIGN_V}$ are intended to make use of the catchment orientation data contained in ASPBAR while eliminating the discontinuity between 359 (one degree west of north) and 0 (north). Definitions of $\mathrm{ALIGN_H}$ and $\mathrm{ALIGN_V}$ using sine and cosine functions were rejected for compressing the range of angular values towards ±1.

3. LONG: A measure of the shape or elongation of the catchment (Equation 3):

Equation 3 – LONG catchment descriptor

$$LONG = \frac{DPLBAR}{AREA}$$

It is noted that LONG is somewhat related to catchment area: all but three of the catchments less than 25 km^2 have values of 0.2 or above, while only one catchment larger than 100 km^2 has a value above 0.2. Using LONG in an SDM will tend to result in selecting catchments with similar sizes. However, there is a range of LONG values at every AREA and, as there appears to be more of a link between L-moments and LONG than between L-moments and AREA, the exact catchments selected for pooling should be more appropriate, even if they are similarly sized to the target catchment.

4. SHAPE: A dimensionless measure equivalent to LONG (Equation 4):

Equation 4 - SHAPE catchment descriptor

$$SHAPE = \frac{DPLBAR^2}{AREA}$$

SHAPE considers catchment elongation, similarly to LONG, but is dimensionless. Therefore, catchments with similarly-shaped outlines will have similar SHAPE values, regardless of how large or small they are.

3. Methodology

3.1 Frequency distribution and parameterisation

The default distribution used for flood frequency estimation in the UK is the generalised logistic (GLO) distribution. Its quantile function is shown in Equation 5:

Equation 5 – Quantile function of the GLO distribution

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

In Equation 5, x_T is the estimated flood peak, ξ, β (= α/ξ) and κ are model parameters and T is return period in years. Estimates of κ and β are found via L-moments as shown in Equations 6 and 7:

Equation 6 – Estimate of κ via L-moments

$$\hat{k} = -t_3$$

Equation 7 – Estimate of β via L-moments

$$\widehat{\beta} = \frac{t_2 \hat{k}\, sin(\pi \hat{k})}{\hat{k}\pi\,(\hat{k}+t_2) - t_2\, sin(\pi \hat{k})}$$

In Equation 7, t_2 and t_3 are the sample L-moment ratios L-CV and L-SKEW respectively (for example, Hosking and Wallis 1997). In pooled analysis, t_2 and t_3 values are, in fact, weighted averages of the t_2 and t_3 values of the sites in the pooling-group. Calculating these weights is detailed in the existing FEH statistical method report (Kjeldsen and others, 2008) and is unchanged here.

3.2 Performance measure

The existing FEH used a pooled uncertainty measure (PUM) to evaluate the performance of potential pooling procedures (Equation 8).

Equation 8 – Evaluating the performance of potential pooling procedures

$$PUM_T = \sqrt{\frac{\sum_{i=1}^{M} W_i (lnx_{t,i} - lnx_{T,i}^{P})^2}{\sum_{i=1}^{M} W_i}}$$

In Equation 8, x_{Ti} is the at-site growth factor at the i'th site and x_{Ti}^{P} is the pooled growth factor at the i'th site. The existing FEH pooling procedure defined w_i as shown in Equation 9, as a compromise measure to give reasonable weights for a large range of return periods. In Equation 9, n_i is the record length in years at catchment i.

Equation 9 – Calculation of W_i for use in Equation 8

$$W_i = \frac{n_i}{1 + n_i / 16}$$

The rationale behind the PUM is that good pooling methods will, on average, produce growth curves that are close to the true growth curve at the site of interest. Kjeldsen and others (2008) defined the true growth curve as the at-site growth curve, and the same definition is used here. The weighting system is used in Equation 8 to reduce the importance of sites where the at-site growth curve is likely to be more uncertain.

This study also considers the heterogeneity of the pooling-groups generated by the new method, measured by the Gini index (Gini 1912) of the at-site t_2 values across a pooling-group of N sites (Equation 10).

Equation 10 – Gini index (from Gini, 1912)

$$G = \frac{1}{N}\left(N + 1 - 2\frac{\sum_{i=1}^{N}(N+1-i)t_2^{(i)}}{\sum_{i=1}^{N} t_2^{(i)}}\right)$$

The Gini index was found by Requena and others (2017) to outperform several other methods for evaluating heterogeneity, including the more-commonly used (in hydrology) *H*-statistic (Hosking & Wallis 1997).

3.3 Similarity distance measure (SDM)

The existing FEH statistical pooling procedure uses a similarity distance measure based on four catchment descriptors: ln(AREA), ln(SAAR), FARL and FPEXT (Equation 11).

Equation 11 – FEH similarity distance measure

$$SDM_{ij} = \sqrt{\begin{array}{l} 3.2\left(\dfrac{lnAREA_i - lnAREA_j}{1.28}\right)^2 + 0.5\left(\dfrac{lnSAAR_i - lnSAAR_j}{0.37}\right)^2 \\ +0.1\left(\dfrac{FARL_i - FARL_j}{0.04}\right)^2 + 0.2\left(\dfrac{FPEXT_i - FPEXT_j}{0.04}\right)^2 \end{array}}$$

In Equation 11, subscript i indicates the target catchment and subscript j indicates a potential pooling-group member. Catchments are added to pooling-groups in order of increasing SDM. Equation 11 was specified as a compromise between two competing requirements: the optimal regression model found for L-CV used ln(AREA), ln(SAAR), FARL and 1–FPEXT, while the optimal regression model found for L-SKEW used ln(AREA), ln(SAAR), 1–FPEXT and AREA untransformed.

Kjeldsen and others (2008) compared the performance of several growth curve estimation methods, including pooling-groups with catchments selected according to similarity; pooling-groups with catchments selected according to geographical proximity; regression equations for L-CV and L-SKEW; and use of a single UK growth curve. It was found that that the pooling-group method, using the SDM specified in Equation 11, only slightly outperformed the regression equation approach. However, using pooling-groups allows a user to update individual catchment L-moments as new AMAX data become available. Converesly, regression models always require refitting in order to incorporate new data.

The original FEH SDM (Institute of Hydrology 1999) used three parameters: ln(AREA), ln(SAAR) and BFIHOST. BFIHOST was not observed to influence L-moments in the study to develop the existing FEH statistical method (Kjeldsen and others, 2008), however it is shown here in Figure 2 to influence L-CV more than many other catchment descriptors.

The existing FEH SDM includes two catchment descriptors, FARL and FPEXT, that were not observed to influence either L-CV or L-SKEW in this small catchment data set. For FARL, this result could be due to the far greater proportion of catchments with FARL at or near 1, relative to the larger data set of 602 catchments against which the FEH SDM was developed. However, a wide range of FPEXT values are observed in this small catchment data set, and a lack of relationship between L-moments and flood plain extent is more likely to relate to the lower importance with regards to flood attenuation of the smaller-sized floodplains in small catchments.

Both SDMs already developed for the FEH statistical method include ln(AREA) and ln(SAAR). While ln(SAAR) is again observed as a strong predictor of L-CV (relative to other catchment descriptors), the same cannot be said for ln(AREA). However, the range of catchment areas in this calibration set is from 0.04 to 40.9 km^2, while in previous studies it is from approximately one to 10,000 km^2. Therefore, it may not be possible to see a link between AREA and L-moments in this study if it only becomes apparent when a larger range of catchment AREA is considered.

3.4 Other aspects of the pooling procedure

The 2008 update to the pooling procedure, detailed in Section 6 of the report that improved the FEH statistical method (Kjeldsen and others, 2008), was subdivided into four tasks:

- forming pooling-groups
- weighting of catchments within pooling-groups
- choosing the total length of pooling-group record
- evaluating performance of the method

These were addressed in order, even though all tasks interrelate, for example, forming a pooling-group requires a decision to be made on how many catchments should be included. Dependencies between the tasks were addressed by performing the tasks cyclically until all outputs were stable.

In this study, the existing FEH recommendations on pooling-group length and catchment weighting within pooling-groups are accepted as is – this study only revisits pooling-group formation, that is, the choice of variables to assess similarity and their weighting. This means that:

- the pooling-group size remains at the minimum required to give 500 station-years of AMAX data
- each catchment's L-moments are weighted according to equations 8.7 to 8.15 of Kjeldsen and others (2008).
- only rural catchments ($URBEXT_{2000} < 0.03$) can be included in a pooling-group
- the default distribution for the flood frequency curve remains as the generalised logistic (GLO) distribution

4. Measuring similarity by visual selection

This section uses visual selection of catchment descriptors to suggest a potential form for a new SDM for small catchments. Statistical performance measures are explored in Section 5.

Plots showing how L-CV and L-SKEW vary in relation to catchment descriptors were presented in Figures 1 to 6 for all 191 study catchments. The smaller, pooling-suitable catchments were plotted with solid shapes to emphasise them, as they meet the definition used in this project for ‘small catchments’ and have the lowest measurement uncertainty in gauged L-moments. In Section 2, it was stated that the only visible relationships were between L-CV and SAAR, RMED13-descriptors, PROPWET, DPSBAR, SPRHOST and BFIHOST, approximately in that order. There were no visible relationships between L-SKEW and any catchment descriptor.

Figure 7 plots L-CV against different transformations of SAAR, PROPWET, DPSBAR, SPRHOST and BFIHOST. The untransformed L-CV values are plotted on the y-axis, while the descriptor and transformation on each x-axis can be read as the intersection of the row title (at the left of each row) and column title (at the top of each column).

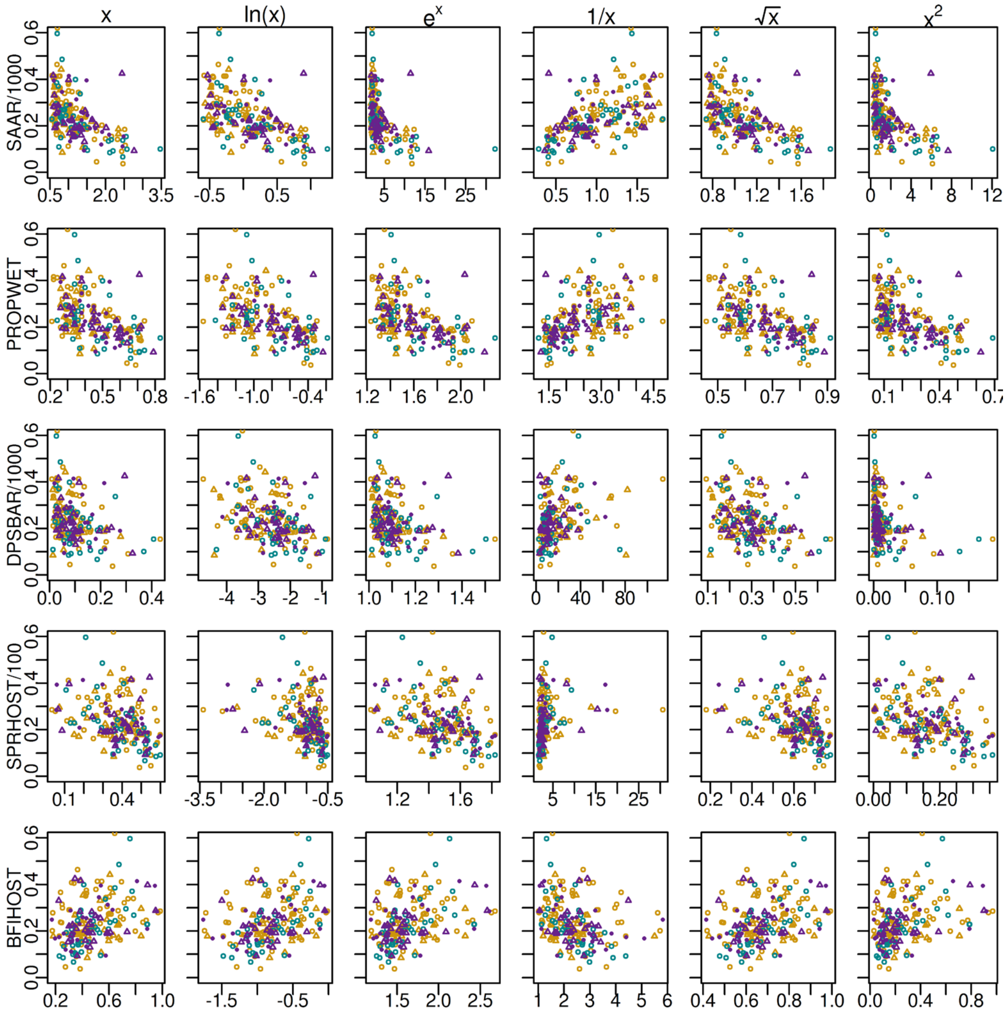

Figure 7 - L-CV vs transformations of catchment descriptors (SAAR, PROPWET, DPSBAR, SPRHOST and BFIHOST)

Figure 7 suggests that a potential two-parameter SDM could be based on ln(DPSBAR) together with either 1000/SAAR or PROPWET/100, while a three-parameter SDM could also include SPRHOST^2 or BFIHOST. Therefore, two parameter sets were tested initially: ln(DPSBAR) with 1/SAAR and ln(DPSBAR) with PROPWET.

4.1 Testing two-parameter SDMs

Table 2 summarises the minimum PUMs achieved on each catchment group with both proposed two-parameter SDMS and the weights required to achieve these PUMs. Bracketed values represent the corresponding PUM achieved by the existing FEH similarity distance measure – ln(AREA) (8.0), ln(SAAR) (1.25), FARL (0.25), FPEXT (0.5), following the same writing convention.

Table 2 - Best visually-selected two-parameter SDMs and corresponding PUMs for different catchment groups

Group	Descriptors (weights)	PUM T=20	PUM T=50	PUM T=100
Pooling <25	1/SAAR (3.25), ln(DPSBAR) (1.0)	0.2790	0.3834	0.4652
Pooling <25	PROPWET (1.0), ln(DPSBAR) (0)	0.2561	0.3538	0.4307
Pooling <25	PUM achieved by the existing FEH similarity distance measure	0.2570	0.3514	0.4252
Pooling >25	1/SAAR (0.5), ln(DPSBAR) (6.75)	0.1864	0.2430	0.2870
Pooling >25	PROPWET (10.0), ln(DPSBAR) (0.5)	0.1654	0.2132	0.2504
Pooling >25	PUM achieved by the existing FEH similarity distance measure	0.1784	0.2309	0.2709
QMED <25	1/SAAR (1.0), ln(DPSBAR) (5.5)	0.3319	0.4510	0.5439
QMED <25	PROPWET (1.0), ln(DPSBAR) (0)	0.3189	0.4375	0.5310
QMED <25	PUM achieved by the existing FEH similarity distance measure	0.3058	0.4140	0.4989
QMED >25	1/SAAR (8.25), ln(DPSBAR) (1.0)	0.2048	0.2827	0.3449
QMED >25	PROPWET (1.0), ln(DPSBAR) (0)	0.2148	0.2914	0.3524
QMED >25	PUM achieved by the existing FEH similarity distance measure	0.2020	0.2776	0.3378
Other <25	1/SAAR (1.0), ln(DPSBAR) (0)	0.3180	0.4252	0.5073
Other <25	PROPWET (1.0), ln(DPSBAR) (0)	0.3100	0.4165	0.4990
Other <25	PUM achieved by the existing FEH similarity distance measure	0.3314	0.4451	0.5321
All groups combined	1/SAAR (1.0), ln(DPSBAR) (0)	0.2866	0.3879	0.4669

Group	Descriptors (weights)	PUM T=20	PUM T=50	PUM T=100
All groups combined	PROPWET (1.0), ln(DPSBAR) (0)	0.2729	0.3715	0.4488
All groups combined	PUM achieved by the existing FEH similarity distance measure	0.2700	0.3646	0.4383

By comparing SDMs across catchment groups, Table 2 shows that the strongest SDM overall is the often the existing FEH measure, which is not specific to small catchments. However, this can be outperformed in certain cases, specifically in the ‘Other <25’ group, ‘Pooling >25’ group and ‘Pooling <25’ group at a 20-year return period, by a measure based either solely on PROPWET or with PROPWET at a much higher weight than ln(DPSBAR). As a result of either varying levels of uncertainty in data quality, varying levels of uncertainty in sampling (record period/length) or variations in the types of catchments in each data set, there is no agreement over which catchment characteristic is more important: while PROPWET is always weighted higher than ln(DPSBAR), SAAR is sometimes weighted lower. However, the general trend is for similarity in wetness to be a better method for selecting pooling-groups than similarity in slope.

Due to the strong performance of PROPWET alone in selecting pooling-groups, two further models were tested: PROPWET with BFIHOST and PROPWET with SPRHOST[2]. PUMs for these measures are shown in Table 3, excluding models that did not outperform PROPWET alone.

Table 3 - Additional two-parameter SDMs and corresponding PUMs

Group	Descriptors (weights)	PUM T=20	PUM T=50	PUM T=100
Pooling <25	PROPWET (0), BFIHOST (1.0)	0.2556	0.3450	0.4145
Pooling <25	PUM using existing FEH statistical SDM (2008)	0.2570	0.3514	0.4252
Pooling >25	PROPWET (3.0), BFIHOST (1.0)	0.1618	0.2087	0.2450
Pooling >25	PROPWET (3.75), $SPRHOST^2$ (1.0)	0.1622	0.2104	0.2485
Pooling >25	PUM using existing FEH statistical SDM (2008)	0.1784	0.2309	0.2709
QMED >25	PROPWET (1.0), $SPRHOST^2$ (4.5)	0.2038	0.2766	0.3338
QMED >25	PUM using existing FEH statistical SDM (2008)	0.2020	0.2776	0.3378

Table 3 reveals some interesting findings, the first of which is that BFIHOST alone is a stronger selection parameter than PROPWET in the subset of catchments most appropriate to the ‘Small catchments’ study. This is not at all obvious from the visual parameter selection method but could result from the relatively strong correlation between BFIHOST and PROPWET across the whole set of 424 potential pooling-group members (cor = −0.55). For the pooling-suitable catchments from 25 to 40.9 km^2, adding either HOST descriptor to the similarity measure results in reduced pooled uncertainty, although the gain over PROPWET alone is marginal. Greater gains can be made by considering $SPRHOST^2$ together with PROPWET for the ‘QMED >25’ group, although the resulting SDM is still less effective than the FEH measure. Finally, for the entire data set of 191 small catchments, no two-parameter SDM tested here is more effective than the one-parameter SDM consisting solely of PROPWET.

4.2 Summary

This section has shown that there is some scope to reduce the uncertainty measure of the pooling-group method for small catchments by developing a new similarity distance measure to select pooling-groups. However, it has also been shown that ‘visual’ selection, that is, looking for patterns in L-moments originating from different catchment descriptors, can be counter-intuitive. Section 5 therefore presents the results of a study in which parameters are selected for a new small catchment SDM through statistical performance measures.

5. Measuring similarity by statistical selection

Figures 1 to 6 show very few strong relationships between L-moments and catchment descriptors, so forward stepwise ordinary least-squares regression was also used to identify which catchment descriptors explain the most variation in observed L-moments for each catchment group. At each stage, the model was extended by adding the catchment descriptor that gave the largest increase in adjusted-R^2 over the previous stage. As the intention of this study was to identify descriptors for an SDM, rather than model the L-moments directly, only the first four descriptors were identified for each catchment group and only ordinary least-squares regression was used, which does not weight calibration data according to uncertainty or account for correlation between calibration data points. Considering the size of each group, there is a risk that including too many descriptors in the forward stepwise regression would result in over-fitting to noise. A log-linear regression was fitted to L-CV, but a linear regression was fitted to L-SKEW as this was found to explain more variance than a log-linear equivalent. The models giving the highest adjusted-R^2 values for different groups of catchments are shown in Tables 4 and 5, where descriptors are listed in order of their addition to the forward stepwise regression.

Table 4 - Catchment descriptors explaining most variation in ln(L-CV) for different catchment groups

Group	Descriptors	Adj-R^2
Pooling <25	SAAR, 1/RMED13-6H, ALIGN$_V$, 1/SHAPE	0.656
Pooling >25	1/PROPWET, 1/FARL, exp(FPDBAR), ALIGN$_V$	0.636
QMED <25	SAAR, 1/AREA, RMED13-6H, exp(LONG)	0.640
QMED >25	1/SAAR, 1/FPEXT, 1/ALTBAR, 1/RMED13-2D	0.569
Other <25	ln(SAAR), 1/ALTBAR, DPSBAR^2, 1/RMED13-6H	0.623
All groups combined	√SAAR, 1/FPDBAR, 1/LDP, 1/DPLBAR	0.490

Table 5 - Catchment descriptors explaining most variation in L-SKEW for different catchment groups

Group	Descriptors	Adj-R^2
Pooling <25	exp(RMED13-2D), $ALIGN_H$, ALTBAR, 1/ASPVAR	0.248
Pooling >25	exp(FPDBAR), $SHAPE^2$, 1/BFIHOST, exp(RMED13-1H)	0.601
QMED <25	exp($ALIGN_H$), exp(RMED13-1H), exp(LONG), ASPVAR	0.154
QMED >25	1/DPSBAR, 1/PROPWET, 1/RMED13-1H, 1/RMED13-2D	0.394
Other <25	$ALIGN_H$, $FARL^2$, 1/FPEXT, exp($ALIGN_V$)	0.176
All groups combined	exp(RMED13-6H), exp($ALIGN_H$), $ALTBAR^2$, 1/SPRHOST	0.106

Models for different catchment groups show very different structures in terms of descriptors and transformations, with the only similarity being the inclusion of SAAR, or the closely related PROPWET, from the very beginning of each model for ln(L-CV). It is noted that BFIHOST was selected very rarely, implying that catchment permeability does not strongly affect the relationships between the relative magnitudes of highly ranked AMAX in a catchment. Models for L-CV tend to explain more variance than models for L-SKEW, which is consistent with Figures 1 to 6 and with earlier work (Robson and Reed 1999, Kjeldsen and others, 2008). However, possibly as a result of the smaller sample sizes, the models here explain substantially more variance – Robson and Reed's models for L-CV and L-SKEW explained just 37.5% and 8% of variance respectively. Kjeldsen and others (2008) did not report the variance explained by their models.

The dissimilarities between the L-CV models for pooling-suitable catchments under and over 25 km^2 may imply that there are some flooding processes unique to small catchments. For example, SHAPE is important in pooling-suitable catchments under 25 km^2, and it is reasonable to suggest that geometry considerations become overpowered by scale considerations in larger catchments. Similarly, flood plain descriptors are important in pooling-suitable catchments over 25 km^2. This observation considers pooling-suitable catchments specifically, as there is more confidence in the data quality of the largest AMAX for these, and it is the largest AMAX that are weighted most strongly in the calculation of L-moments.

Models derived here for L-SKEW are very mixed in terms of descriptors, with few similarities between those selected for different catchment groups. This is consistent with the extremely limited variance explained in Robson and Reed's model, as in all cases, random, unexplained variance is the main source of differing values of L-SKEW.

5.1 Development of SDM

A two-parameter SDM was identified for each catchment group by searching through all combinations of catchment descriptors shown to have some statistical influence over either ln(L-CV) or L-SKEW, and evaluating the resultant PUM for T = 20, 50 and 100 years. Each two-parameter SDM was tested first with the weight of the second parameter set to one and the weight of the first parameter stepped from 0 to 10 in 0.25 increments, then with the weightings applied oppositely. The lowest PUM, which could normally only be achieved with one combination of weights, was saved for each two-parameter SDM.

Table 6 shows the lowest two-parameter PUMs achieved for each catchment group, and the descriptors and weights used to achieve that PUM. Bracketed values represent the corresponding PUM achieved by the existing FEH similarity distance measure – ln(AREA) (8.0), ln(SAAR) (1.25), FARL (0.25), FPEXT (0.5).

Table 6 - Best statistically selected two-parameter SDMs and corresponding PUMs for different catchment groups

Group	Descriptors (weights)	PUM T=20	PUM T=50	PUM T=100
Pooling <25	AREA (5.5), RMED13-1D (1.0)	0.2392	0.3267	0.3958
Pooling <25	PUM for existing FEH statistical SDM	0.2587	0.3530	0.4266
Pooling >25	exp(FARL) (2.75), 1/PROPWET (1.0)	0.1588	0.2093	0.2497
Pooling >25	PUM for existing FEH statistical SDM	0.1736	0.2247	0.2639
QMED <25	SAAR (2.5), ln(AREA) (1.0)	0.2851	0.3918	0.4763
QMED <25	PUM for existing FEH statistical SDM	0.3063	0.4147	0.4997
QMED >25	ln(SAAR) (5,75), exp($ALIGN_H$) (1.0)	0.1833	0.2524	0.3076
QMED >25	PUM for existing FEH statistical SDM	0.2054	0.2815	0.3419
Other <25	$SPRHOST^2$ (1.25), AREA (1.0)	0.2930	0.3910	0.4659
Other <25	PUM for existing FEH statistical SDM	0.3337	0.4480	0.5354
All groups combined	ln(AREA) (1.25), SAAR (1.0)	0.2592	0.3508	0.4224
All groups combined	PUM for existing FEH statistical SDM	0.2708	0.3655	0.4393

The statistical selection of PUMs shows that AREA or ln(AREA) is selected for all three groups containing only catchments under 25 km^2 and for the whole data set of 191 catchments. In all cases except ‘Pooling <25’, the weight applied to AREA is similar to the weight of the other catchment descriptor. However, for ‘Pooling <25’, AREA receives a far higher weight than RMED13-1D. This is particularly noteworthy as this group is composed solely of catchments that are both defined as strictly small and as having the smallest measurement uncertainty in L-moments.

Consistently selecting AREA as a main criterion for selecting from the 424 potential pooling-group members shows that the main benefit of including small catchments in small catchment pooling-groups normally derives from their small size – the purpose of including SHAPE and LONG as potential descriptors was to differentiate longer, thinner, valley-type small catchments from others. However, if the calibration data set contains few of that type, other catchment descriptors that are more important to other types of small catchment will have more of an influence in the PUM.

Comparison of PUMs within each group (that is, those achieved by the new measure versus those achieved by the FEH measure) show that the benefit of using a different PUM for small catchments is small but consistent. Comparison of SDM structures across the groups suggests that an optimal form for small catchments contains ln(AREA) and SAAR untransformed. Figure 8 shows how the PUM varies as the weight of either ln(AREA) or SAAR is varied from 0 to 10, for all 191 study catchments. Figure 9 shows the same for the ‘Pooling <25’ group. The weight of the parameter not being varied is held at one in all cases.

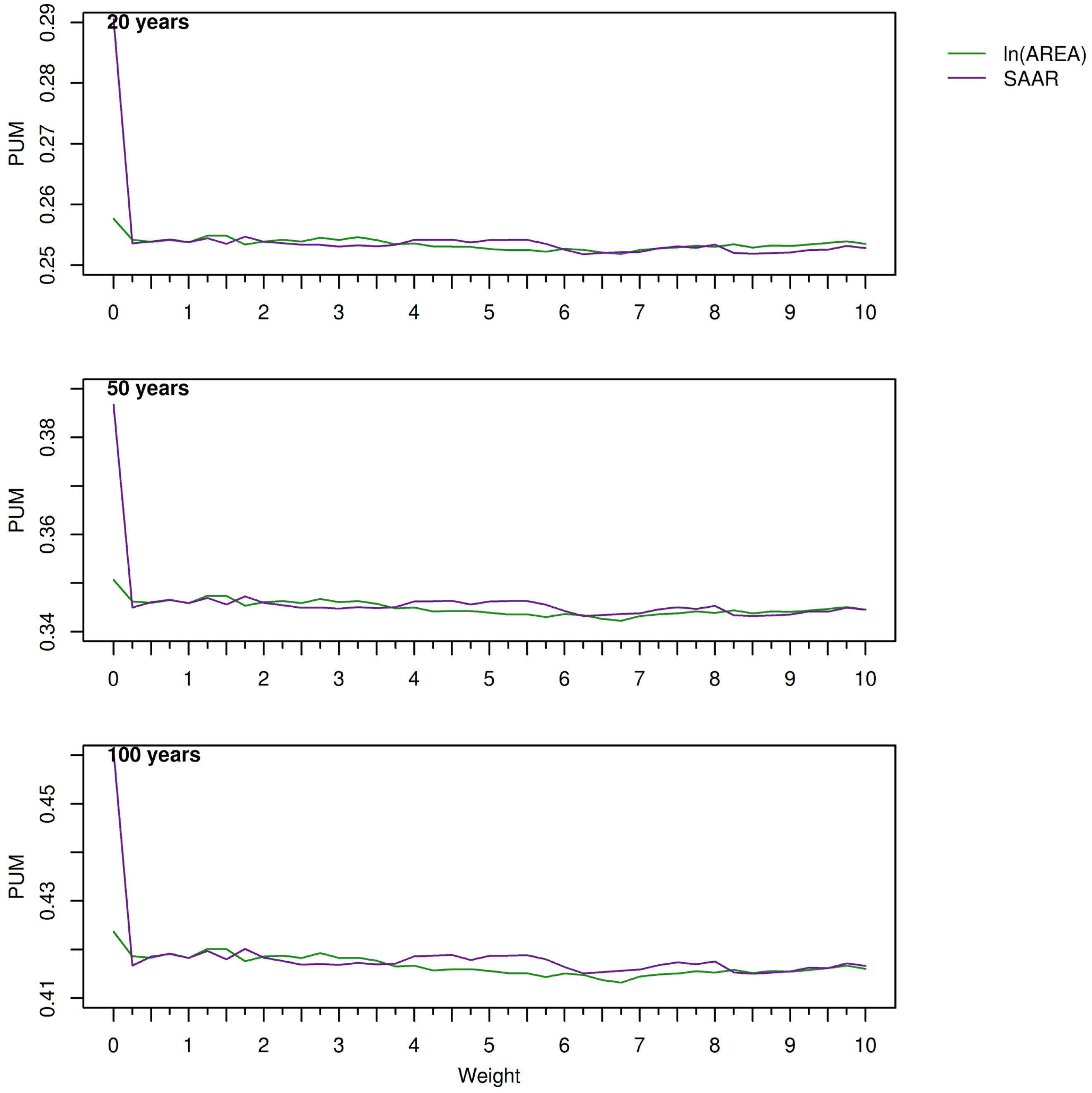

Figure 8 - Variation in PUM with SDM parameter weights, full calibration data set for the 1 in 20 year, 1 in 50 year and 1 in 100 year return periods

The three graphs in Figure 8 plot the weights applied to SAAR (purple line) and ln(AREA) (green line) from 0 to 10 (on the x-axis), when the other's weight is fixed at 1. The y-axes show the corresponding PUM:

- top graph: the y-axis plots PUM from 0.25 to 0.29
  middle graph; the y-axis plots PUM from 0.34 to 0.38
- bottom graph: the y-axis plots PUM from 0.41 to 0.45

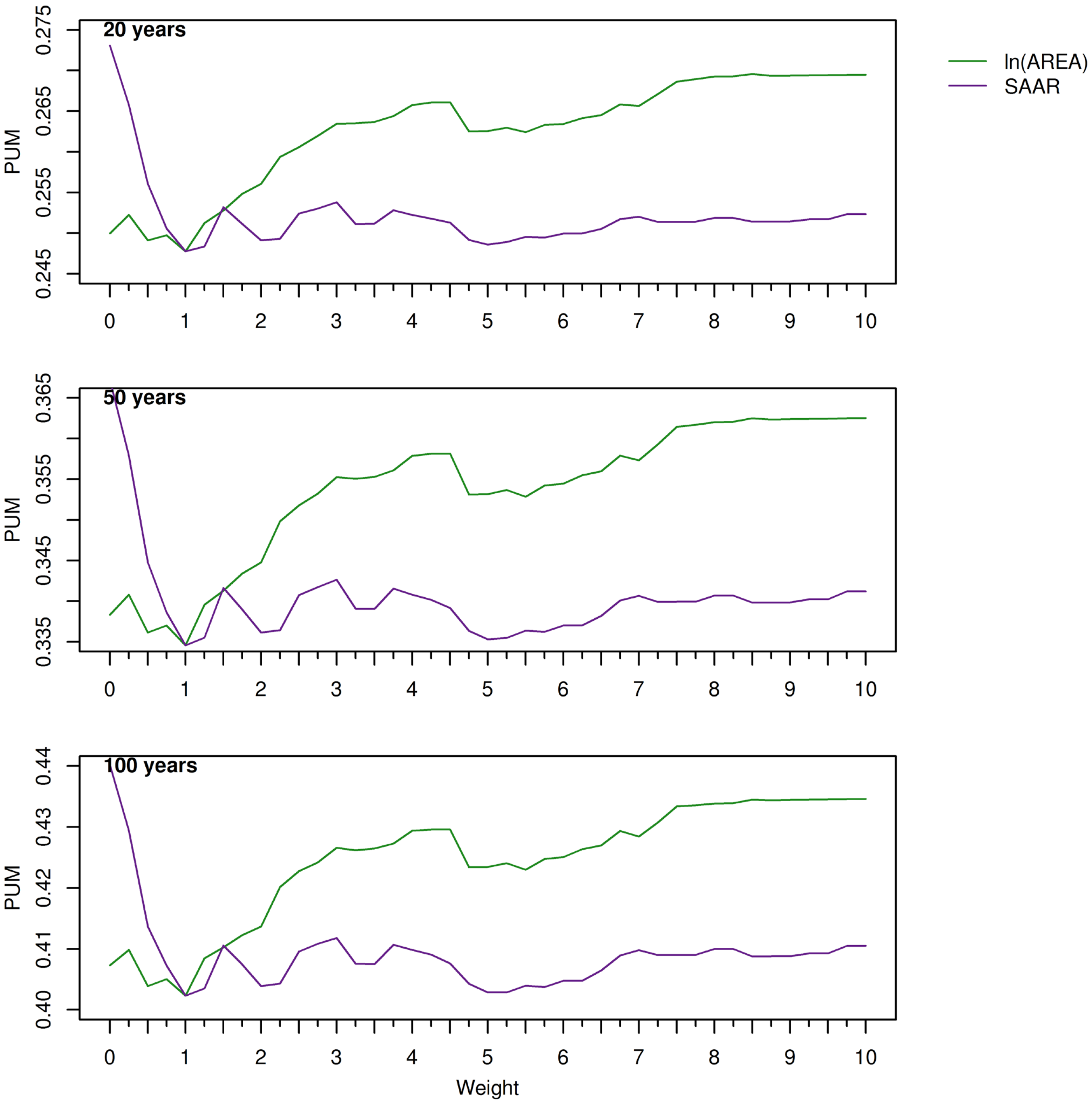

Figure 9 - Variation in PUM with SDM parameter weights, ‘Pooling <25’ group for the 1 in 20 year, 1 in 50 year and 1 in 100 year return periods

The three graphs in Figure 9 plot the weights applied to SAAR (purple line) and ln(AREA) (green line) from 0 to 10 (on the x-axis) , when the other’s weight is fixed at 1. The y-axes show the corresponding PUM:

- top graph: the y-axis plots PUM from 0.245 to 0.275
- middle graph; the y-axis plots PUM from 0.335 to 0.365
- bottom graph: the y-axis plots PUM from 0.40 to 0.44

Both Figure 8 and Figure 9 show that SAAR is more important than ln(AREA) in selecting a pooling-group. This finding is consistent with the existing FEH measure, in its choice of the two most important descriptors. Figure 8 shows that the exact weight assigned to each parameter is relatively unimportant, while Figure 9 advises that the optimal weight for both parameters is one – both should be weighted equally. As the SDM considered in Figure 9 produces lower PUM values than the existing FEH measure, it is implied that a selection process based on only AREA and SAAR is superior to one based on AREA, SAAR, FARL and FPEXT. However, any observation or conclusion relating to FARL is complicated by the reduced range of FARL values in this calibration data set relative to gauged catchments in the UK as a whole.

A three-parameter SDM is tested on the ‘Pooling <25’ group and full data set, using the two-parameter SDM with ln(AREA) and SAAR as a base. Table 7 shows the best resulting three-parameter SDMs for these two groups of catchments. The PUMs achieved through ‘cross-applying’ (that is, using the ‘Pooling <25’ SDM on all catchments and vice versa) are bracketed underneath.

Table 7 - Best statistically selected three-parameter SDMs and corresponding PUMs

Group	Descriptors (weights)	PUM T=20	PUM T=50	PUM T=100
Pooling <25	ln(AREA) (0.25), SAAR (4.0), 1/PROPWET (4.5)	0.2302	0.3190	0.3897
Pooling <25	PUM for ‘cross applied’ SDM	0.2413	0.3289	0.3977
All groups combined	ln(AREA) (3.0), SAAR (3.25), exp(FARL) (0.75)	0.2553	0.3461	0.4172
All groups combined	PUM for ‘cross applied’ SDM	0.2668	0.3641	0.4404

Both three-parameter SDMs reduce uncertainty in their respective data sets. However, the performance of the three-parameter ‘All groups combined’ SDM is no better than that shown in Figure 8 for the two-parameter measure with ln(AREA) and SAAR at equal weight. Additionally, cross-application of the two SDMs given in Table 7 does not offer a worthwhile improvement over the two-parameter SDM, in terms of PUM, when the sampling uncertainty inherent in such a small dataset is considered. Furthermore, the weights applied to ln(AREA) and SAAR in the ‘Pooling <25’ SDM are not equal, while for the ‘All groups combined’ SDM, they approximately are. Together with the correlation between SAAR and PROPWET, the ‘Pooling <25’ SDM appears to be reverting to its own optimal weights, which are far from the more equal weights proposed for the two-parameter SDM.

At this stage, therefore, the provisional new SDM for small catchments uses two parameters, ln(AREA) and SAAR, weighted equally. The Gini index of pooled t_2 values was calculated for each pooling-group generated by the new SDM and existing SDM; the cumulative distribution of Gini indices for all 191 catchments is shown in Figure 10.

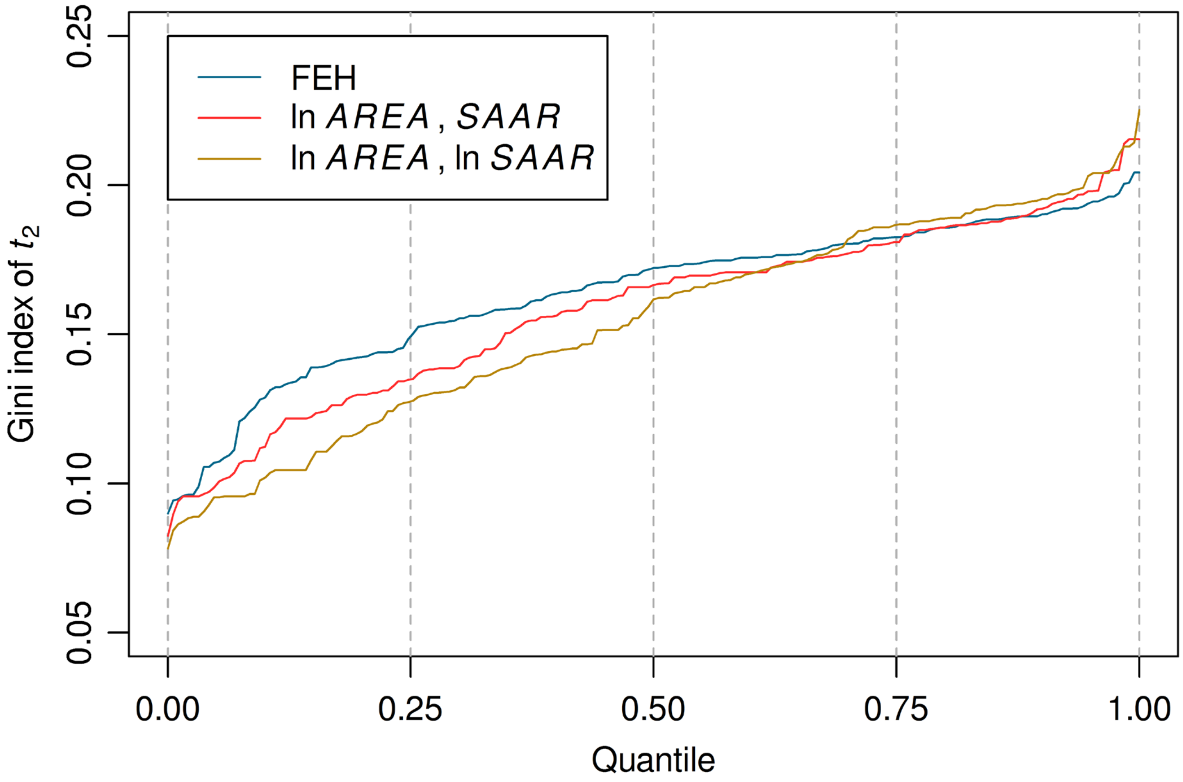

Figure 10 - Cumulative distribution of Gini index of t_2 for pooling-groups selected using the FEH SDM, and new SDMs based on ln(AREA), SAAR and ln(AREA), ln(SAAR) with equal weighting

The x-axis of the line graph in Figure 10 shows the quantile (from 0.00 to 1.00). The y-axis shows the Gini index of t_2 from 0.05 to 0.25. The lines plot different SDMs:

- FEH (blue line)
- ln(AREA), SAAR (red line)
- ln(AREA), ln(SAAR) (gold line)

Figure 10 also reviews a third SDM, based around ln(AREA) and ln(SAAR) at equal weight. Both two-parameter SDMs are found to create pooling-groups with greater homogeneity than when the FEH measure is used. Additionally, pooling-groups created using the SDM with ln(SAAR) have considerably lower Gini indices in t_2 than those created using either other SDM for the majority of test catchments, with only slightly higher Gini indices for the catchments with the most heterogeneous pooling-groups.

5.2 Proposed SDM for small catchments

The final proposed SDM for small catchments is presented in Equation 12, and is based on the catchment descriptors ln(AREA) and ln(SAAR) at equal weight:

Equation 12 – Final proposed SDM for small catchments

$$SDM_{ij} = \sqrt{\left(\frac{ln\,AREA_i - ln\,AREA_j}{1.264}\right)^2 + \left(\frac{ln\,SAAR_i - ln\,SAAR_j}{0.349}\right)^2}$$

‘Heat maps’, showing the amount of similarity between pooling-groups for different catchments, are presented in Figures 11 to 14. Figures 11 and 12 compare the similarity in pooling-groups for the 28 catchments smaller than 25 km^2 and deemed suitable for pooling, while Figures 13 and 14 compare the similarity in pooling-groups across all 191 study catchments. A similarity of zero means that two catchments do not share any pooling-group members and a similarity of one means that two catchments share all pooling-group members. The arrangement of catchments along the axes is designed to reveal the largest clusters of catchments sharing pooling-group members – there is no hydrological reason behind the ordering.

In general, both the existing FEH and Equation 12 SDMs produce some clustering. This is expected, as both similarity distance measures consider AREA, therefore smaller catchments are preferred in both pooling-group selection measures. However, there is more white space and a lower mean similarity index on Figures 12 and 14 (showing the performance of Equation 12) in comparison to Figures 11 and 13 (showing the performance of the FEH measure). The comparative increase in white space on Figures 12 and 14 means that there are fewer catchments common to more pooling-groups when compared to the Equation 12 measure. Additionally, there are fewer dark squares, showing fewer catchments with near-identical pooling-groups. This means that two pooling-groups for two arbitrary catchments will typically be more different when they are selected by Equation 12 than by the existing FEH measure.

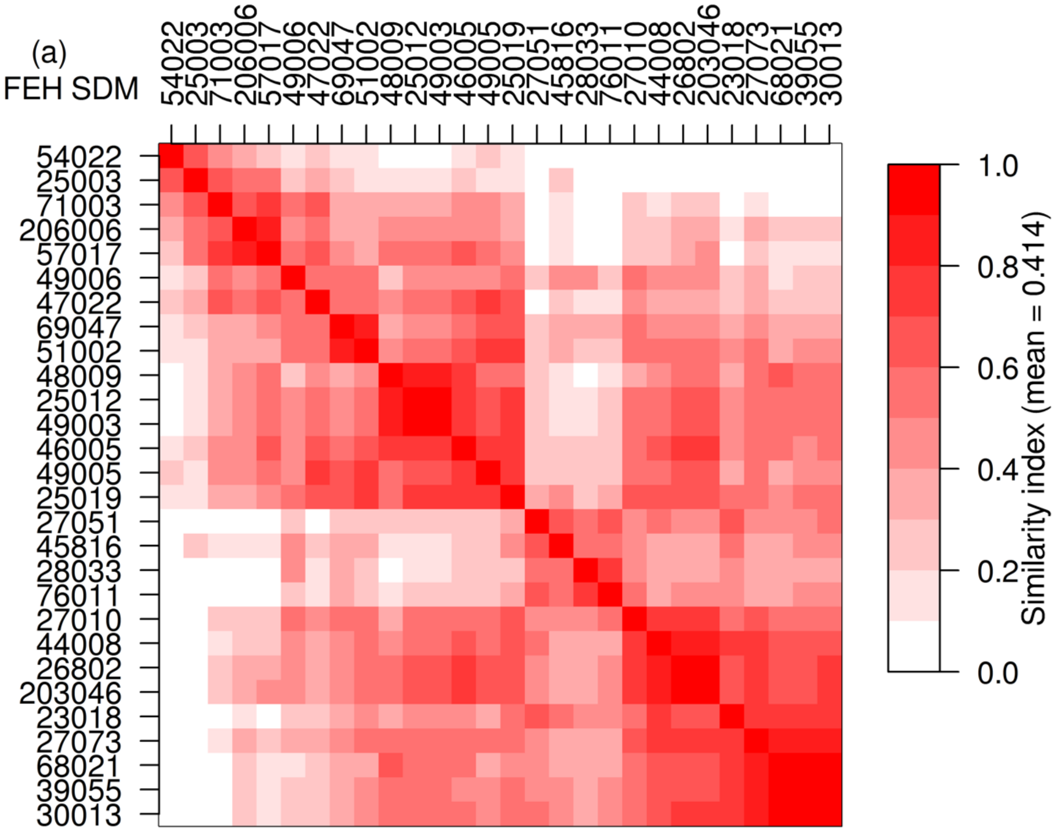

Figure 11 - Similarity heat map for ‘Pooling <25’ group (FEH measure)

The heat map in Figure 11 shows the similarity in pooling-groups for the 28 catchments smaller than 25 km^2 and deemed suitable for pooling based on a similarity index (mean = 0.414) ranging from 0.0 (white) to 1.0 (dark red).

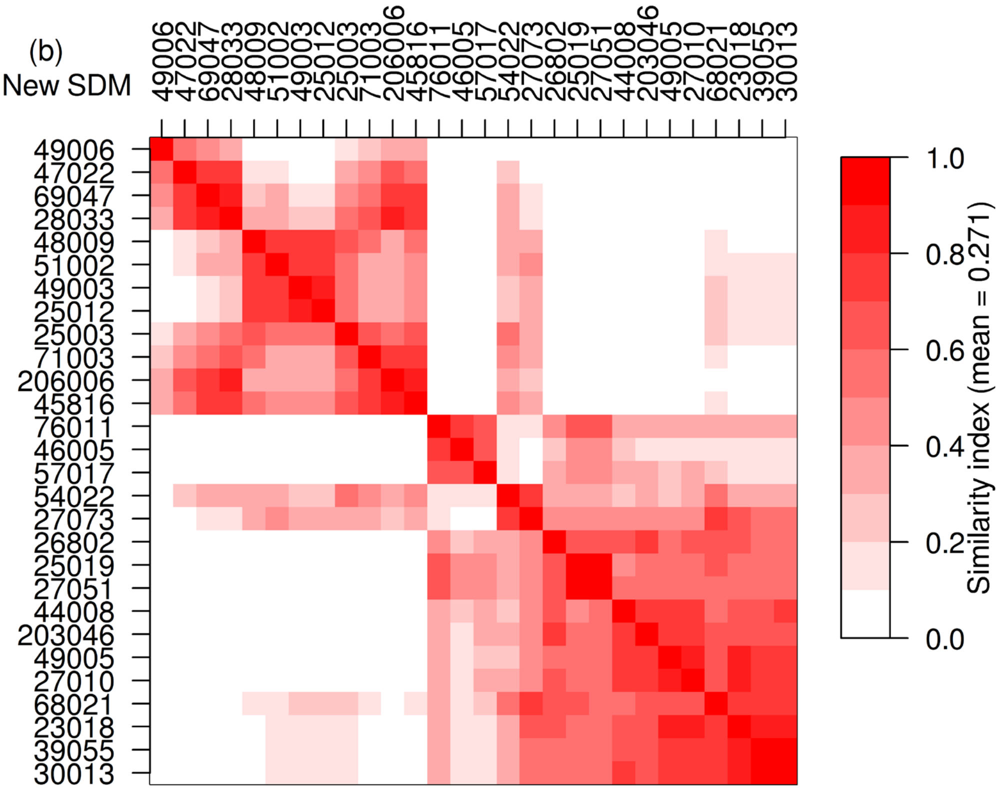

Figure 12 - Similarity heat map for 'Pooling <25' group (performance of Equation 12)

The heat map in Figure 12 shows the similarity in pooling-groups for the 28 catchments smaller than 25 km^2 and deemed suitable for pooling based on a similarity index (mean = 0.271) ranging from 0.0 (white) to 1.0 (dark red).

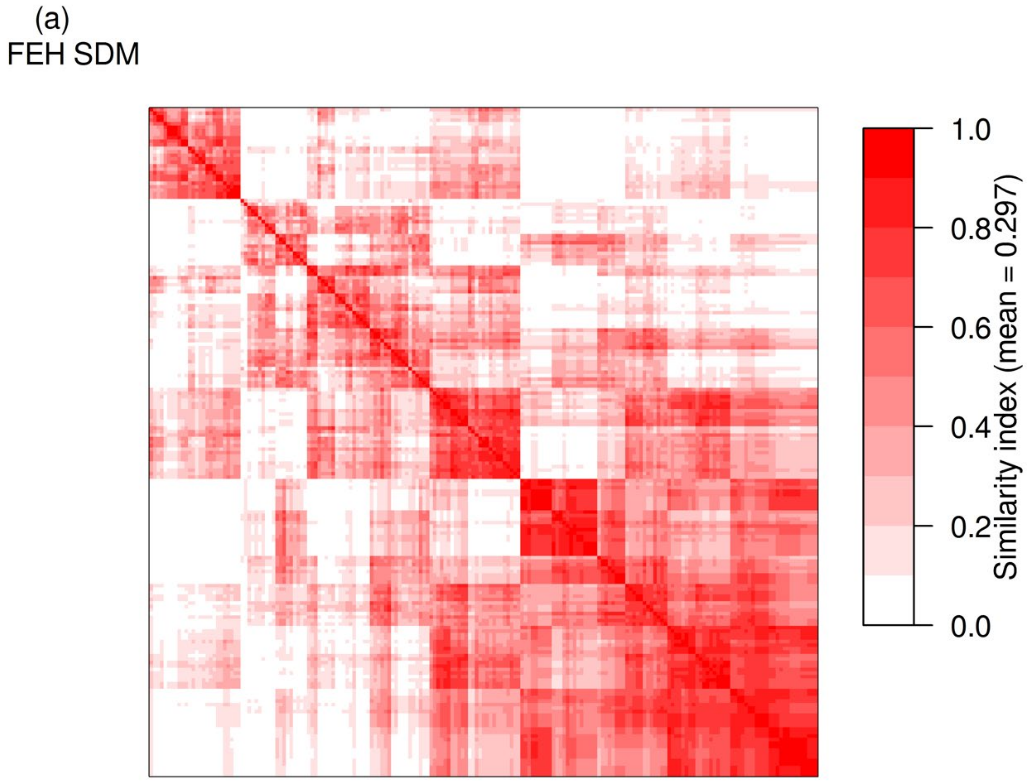

Figure 13 - Similarity heat maps for all study catchments (FEH measure)

The heat map in Figure 13 shows the similarity in pooling-groups across all 191 study catchments based on a similarity index (mean = 0.297) ranging from 0.0 (white) to 1.0 (dark red).

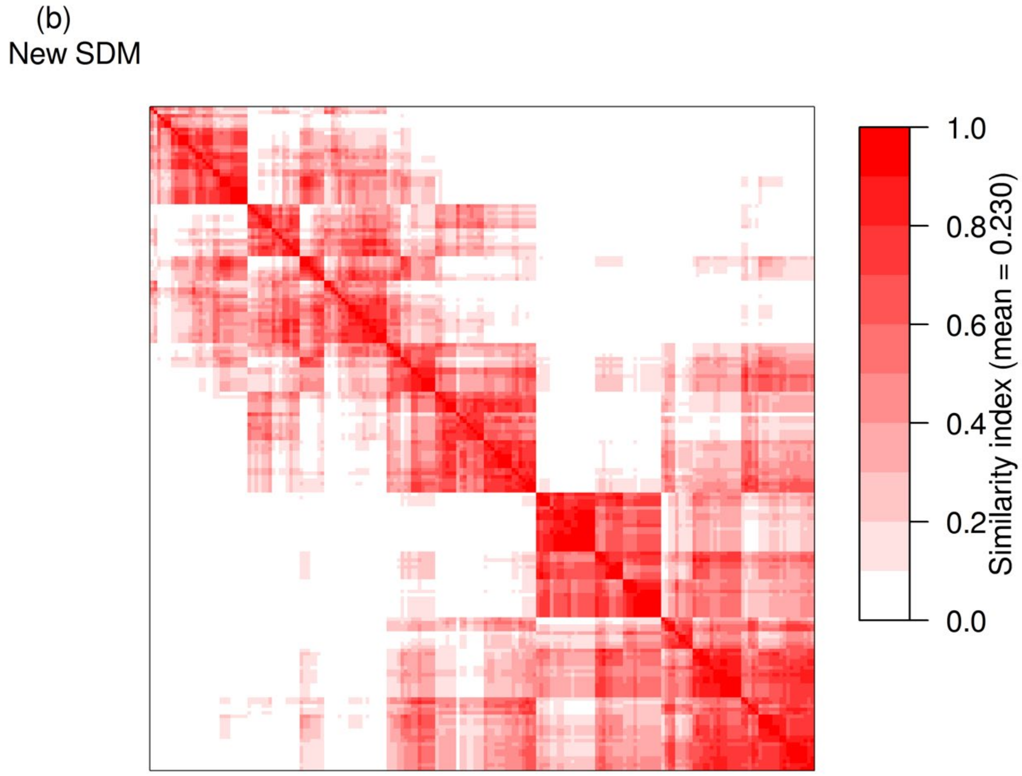

Figure 14 - Similarity heat map for all study catchments (performance of Equation 12)

The heat map in Figure 14 shows the similarity in pooling-groups across all 191 study catchments based on a similarity index (mean = 0.230) ranging from 0.0 (white) to 1.0 (dark red).

Figure 15 demonstrates the relationship between at-site and pooled 100-year growth factor for the FEH SDM (left) and new SDM (right). While both measures result in maximum 100-year growth factors of about 3.4 (in contrast to a maximum at-site value of about 20), the new measure results in a greater range of pooled growth factors, with considerably more in the 1.8 to 2.5 range and relatively fewer compressed into the 2.5 to 3.0 range. In addition, pooled and at-site growth seem to correspond more closely when the new SDM is used – the range of points is more ‘triangular’ on the right plot, with more points lying closer to the dotted 1:1 line. New growth factors are generally decreased where the FEH growth factor was an overestimate of the at-site growth factor, and slightly increased where the FEH growth factor was an underestimate of the at-site growth factor. However, as the FEH growth factor was larger than the at-site growth factor in most cases, using the new small catchment growth factor will result in a reduction of the 100-year flood peak more frequently than it will result in an increase. The inability of either measure to produce high growth factors to match the few at-site growth factors in the five to 20 range is not considered problematic, as it is generally expected that these outlying growth factors will reduce as more annual maxima are collected at those stations. Indeed, the reason for pooling data at gauged stations, rather than using gauged estimates alone, is to mitigate sampling errors inherent in the finite at-site record. The requirement that all flows are nonnegative limits the range of possible distributions to those with κ ≤ –β in the long-term. Additionally, it can be noted that 100-year growth factors above five correspond almost entirely to catchments deemed unsuitable for pooling, meaning that the high growth factors can almost certainly be attributed in part to insufficient hydrometric design. These very high at-site growth factors demonstrate why stations not marked as ‘suitable for pooling’ should not be included in pooled or enhanced single-site analyses.

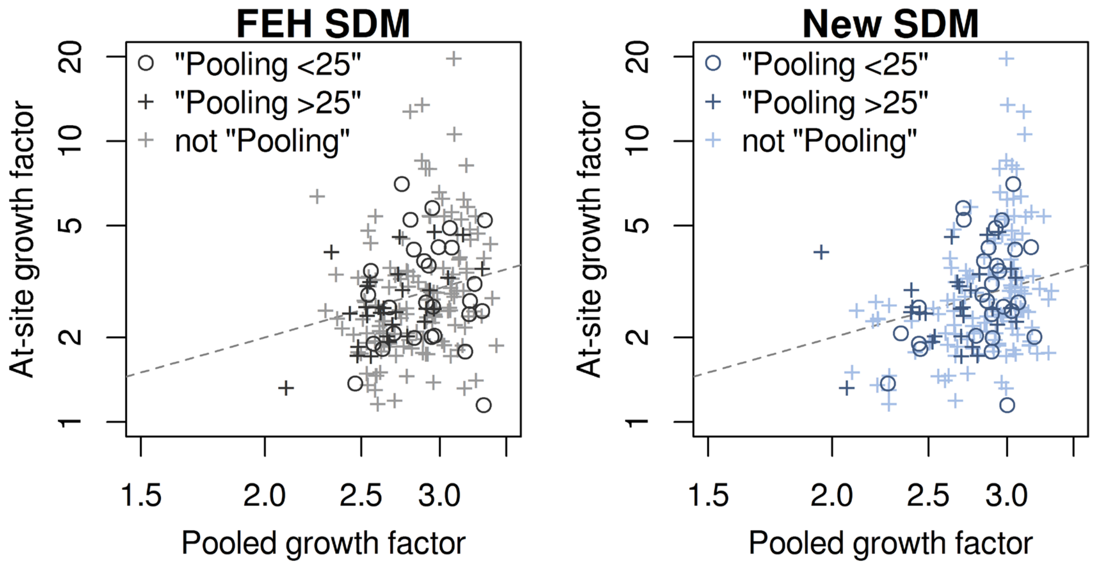

Figure 15 - 100-year growth factors estimated by FEH and new SDMs compared to 100-year at-site growth factors

The two scatter graphs in Figure 15 show the relationship between at-site and pooled 100-year growth factor for the FEH SDM (left-hand graph) and new SDM (right-hand graph). The x-axis on both graphs shows the pooled growth factor (from 1.5 to 3.0) and the y-axes show the at-site growth factor (from 1 to 20). Plotted on both graphs are:

- “pooling <25”: black circles (FEH SDM graph) and blue circles (new SDM graph)
- “pooling >25”: black crosses (FEH SDM graph) and dark blue crosses (new SDM graph)
- not “pooling”: grey crosses (FEH SDM graph) and light blue crosses (new SDM graph)

6. Conclusions and recommendations

A new similarity distance measure (SDM) for small catchment pooling-groups was developed in this report and presented in Equation 12. Despite sharing AREA and SAAR with the existing FEH measure to select potential pooling-group members, it is far simpler, relying on no other catchment descriptors, and it gives equal weight to both ln(AREA) and ln(SAAR). By reducing the dependence on AREA in selecting pooling-groups, the resulting pooling-groups for arbitrary small catchments are more dissimilar. This is considered advantageous, due to the wide range of small catchment types in the UK. In addition, the reduced pooled uncertainty measure (PUM) and Gini index of t_2 compared to the existing FEH SDM measure shows that the two-parameter SDM developed here and presented in Equation 12 is more appropriate to statistical design flood estimation in small catchments.

For forming pooling-groups for small catchments (up to 40 km^2), the following recommendations therefore apply:

- potential pooling-group members should be selected according to the revised small-catchment similarity distance measure, presented in Equation 12 and repeated below (Equation 13):

Equation 13 - Final proposed SDM for small catchments

$$SDM_{ij} = \sqrt{\left(\frac{\ln AREA_i - \ln AREA_j}{1.264}\right)^2 + \left(\frac{\ln SAAR_i - \ln SAAR_j}{0.349}\right)^2}$$

- potential pooling-group members should not be restricted in terms of catchment area
- pooling-groups should be verified: if any catchment presents significantly different L-moments from others, the cause of this should be investigated and, if appropriate, the catchment removed
- all parts of the pooling procedure other than the similarity distance measure remain unchanged

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List of abbreviations

AMAX	Peak instantaneous annual maximum flow
FEH	Flood Estimation Handbook
GLO	Generalised logistic distribution
HOST	Hydrology of soil types
IHDTM	Integrated Hydrological Digital Terrain Model
MORECS	Met Office Rainfall and Evapotranspiration Calculation System
NRFA	National River Flow Archive
PUM	Pooled uncertainty measure
QMED	Median annual flood, normally estimated as median of AMAX series
SDM	Similarity distance measure

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