Estimating flood peaks and hydrographs for small catchments:

R0 – Phase 2 overview report

FCERM Research & Development Programme

Research Report

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Executive summary

Flood frequency estimation in small catchments, generally defined as having an area less than about 25 km^2, is an important part of flood risk management in the UK, because most UK catchments are small. Flood risk assessments are needed to meet the requirements of planning policy and for flood mapping and modelling studies. This project has looked at how appropriate current flood estimation techniques are when applied to small catchments down to small plots of land, which may not even contain a watercourse.

Sections 1-4 of this report provide an overview of the project's background, aims, conclusions and recommendations, with supporting evidence and worked examples showing how to apply the latest best practice methods in small catchments. Sections 5-14 give an overview of the main findings and recommendations of each the nine main studies carried out during the project.

This project has reassessed the most recent generation of Flood Estimation Handbook (FEH) methods (IH 1999; Kjeldsen and others*,* 2008; Wallingford HydroSolutions 2016a) at the time of investigation against a newly developed data set of peak flows in catchments less than 41 km^2.

Following this, several new methods tailored to small catchments have been developed, although not all provide enough of an improvement over existing all-catchment methods to be recommended.

For statistical estimation, a new median annual flood (QMED) equation was produced. However, the current equation (Kjeldsen and others, 2008) continues to be recommended for all fluvial catchments, regardless of area. For catchments up to 25 km^2, adjusting the QMED equation estimate using the single closest donor catchment rather than several is recommended. For floods other than QMED, a new similarity distance measure (SDM) has been developed to create an appropriate pooling-group.

Hydrographs produced by the second version of the revitalised flood hydrograph method (ReFH2) have been compared with those derived by Archer and others' (2000) empirical method and have been found to be broadly appropriate for most catchment types. Current design inputs to ReFH2 were reviewed and new modelling guidance has been developed for urban catchments of all sizes. In addition, the estimate of unit hydrograph time-to-peak, T_p, in small catchments and plots has been reviewed.

The project has also shown that FEH methods are more appropriate than some widely used, but outdated methods for estimating plot-scale runoff rates and volumes.

To help practitioners reduce their reliance on methods such as IH124 and ADAS 345, a free, open-source screening data set has been produced. The project has calculated greenfield runoff rates and volumes for specific return periods across England and Wales. The data, which was produced from methods which draw upon open-source data, still exhibits more uncertainty than full FEH methods, and are intended for use as a screening tool only, for the pre-planning stage of new developments.

Other analyses carried out during the project are reported in Sections 5-14 and in a series of technical reports.

It is important to note that the recommendations in this report can be generally applied to the whole of UK. However, in line with other guidance on flood estimation, practitioners should always seek as much relevant information on local circumstances as possible and exercise judgement when using generalised methods. Further advice is provided in the Environment Agency’s project ‘Making better use of local data in flood frequency estimation’ (Environment Agency 2017). The methods and approaches in this research report are not intended to be followed as guidance. This report should not replace flood estimation guidance or expert judgement; users should always consider these against the wider context.

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.

FEH catchment descriptors

The following are the main catchment descriptors used throughout the analyses described in this report.

AREA	Catchment drainage area (km^2)
BFIHOST	Baseflow index derived using the HOST classification
DPLBAR	Index describing catchment size and drainage path configuration (km)
DPSBAR	Index of catchment steepness (m/km)
FARL	Index of flood attenuation due to reservoirs and lakes
FPEXT	Fraction of the catchment inundated by the 100-year flood
PROPWET	Index of proportion of time that soils are wet
RMED13-1H	1-hour, 2-year rainfall depth from FEH13 rainfall model (mm)
RMED13-6H	6-hour, 2-year rainfall depth from FEH13 rainfall model (mm)
RMED13-1D	1-day, 2-year rainfall depth from FEH13 rainfall model (mm)
RMED13-2D	2-day, 2-year rainfall depth from FEH13 rainfall model (mm)
SAAR	1961 to 90 standard period average annual rainfall (mm)
SPRHOST	Standard percentage runoff derived using the HOST classification (%)
$URBEXT_{2000}$	Weighted coverage of urban, suburban and inland bare ground as a proportion of the catchment derived from the Land Cover Map 2000

1. Introduction

This report assumes that the reader is familiar with the basic concepts of the Flood Estimation Handbook (FEH) methods (IH 1999; Kjeldsen 2007; Kjeldsen and others, 2008; Environment Agency 2020) and how they are put into practice for flood risk assessment in the UK. Definitions of the most widely used terms and appropriate references are provided throughout.

The project has addressed the question of how well existing FEH methods of flood estimation perform in small fluvial catchments (defined in general as areas smaller than about 25 km^2) and plots of land (often less than one hectare in area) for which estimates of peak flow runoff rates and volumes are required. The report provides clear guidance on using both statistical and design hydrograph (rainfall-runoff) methods in small catchments and plots, together with references to the technical reports that provide details of the data and analyses. In addition, a new set of estimated plot-scale runoff rates and volumes for preliminary screening key return periods has been mapped across England and Wales. The recommendations for best practice in small catchments and plots are accompanied by several worked examples.

1.1 Background

The aim of phase 2 of Project SC090031 ‘Estimating flood peaks and hydrographs for small catchments’ was to develop improved techniques for flood estimation in small UK catchments, including peak flows and hydrographs. The project was led by the Centre for Ecology & Hydrology (CEH), and involved practical input and guidance from JBA Consulting, Wallingford HydroSolutions (WHS) and David MacDonald (Independent consultant). The overall objective of the project was to allow hydrologists and engineers to produce flood estimates for small fluvial catchments and plot-scale areas with less uncertainty than is currently possible.

Phase 1 of the project was a scoping study, the results of which are reported by the Environment Agency (2012). The phase 1 analysis concluded that the then-existing FEH methods (the FEH statistical and ReFH1 methods) are more appropriate for flood estimation in small catchments than other widely used techniques such as ADAS 345 (ADAS 1982) or IH124 (Marshall & Bayliss 1994). However, the flood response of highly permeable and/or urbanised catchments was identified as being more difficult to characterise. The main recommendations of phase 1 led to the definition of the following objectives for phase 2:

- building an expanded data set of small catchments peak flow data
- developing improved methods to model flood flows in small ungauged catchments and plots
- further review and recommendations

A specific requirement of the project was to develop a new method based on freely available data to derive design standard peak flow estimates to inform greenfield runoff calculations for 12-month, 30-year and 100-year return periods.

1.2 Overview of report

This report presents a summary of the phase 2 project, focusing particularly on the research outcomes and recommendations that can be put into practice for flood and runoff estimation in small catchments and plots in the UK. The report is presented in two parts: Sections 1-4 provide an overview of the project's background, aims, conclusions and recommendations, with supporting evidence for those recommendations and worked examples showing how to apply current best practice in small catchments. Sections 5-14 provide an overview of the main studies carried out during the project, and each section provides a condensed version of a full technical report produced during the course of the project.

The research started from the interim recommendation made in the report of phase 1 of the project that flood estimates for small catchments should be derived from FEH methods rather than from several outdated methods that are still used (Environment Agency 2012). A new data set of peak flows in small catchments was developed and a baseline assessment of the performance of existing FEH methods was carried out, leading to the following recommendations:

- a new catchment descriptor equation to estimate QMED, the median annual maximum flood, at ungauged locations specifically tailored to small catchments (generally defined as catchments of less than 25 km^2) should be developed and tested
- the potential for developing a new pooling procedure to estimate floods of longer return periods in small catchments should be explored
- the form of design hydrograph resulting from the FEH's rainfall-runoff method known as the ReFH design package (Kjeldsen 2007; Wallingford HydroSolutions 2016a) should be investigated to assess how appropriate it is
- clarification on the recommended design inputs to the ReFH package should be given

As a result, several complex analyses using the small catchment data set were carried out, leading to the development of a range of new methods for estimating QMED. However, a subsequent evaluation exercise concluded that not all the new methods can be recommended for practical use. A revised pooling procedure to improve the estimation of flood quantiles greater than QMED was developed and is recommended for application in small catchments. The analysis of hydrograph shape and investigation of alternative design inputs to the ReFH2 method have led to several recommendations.

During its early stages, the project also investigated the potential for improving flood estimates by taking local data, such as vegetation type and land management into account. This investigation was greatly extended and published as part of a different project: 'Making better use of local data in flood frequency estimation' (Environment Agency 2017). In addition, because small catchments often have short response times and are potentially vulnerable to short, intense bursts of rainfall, the depth-duration-frequency characteristics of short duration rainfall data were studied and the reliability of current (at the time of study) national models in estimating the frequency of very short duration rainfall was evaluated.

The ReFH2 rainfall-runoff model received a major update during (but outside of) this project, the most significant aspect of which was the ability to use rainfall estimates from the FEH13 rainfall model as inputs. As a result, work carried out earlier in this project used the then-current implementation of ReFH2 with FEH99 rainfalls (ReFH2-FEH99) and later work used the implementation of ReFH2 with FEH13 rainfalls (ReFH2-FEH13). Some earlier work also used the original ReFH (ReFH1) model to provide further confirmation that it should be considered superseded by ReFH2. Table 1 summarises which variants of ReFH were used in which sections of this report and in which project reports.

Table 1 - Summary of ReFH variants used in project

Section & Report(s)	ReFH1	ReFH2-FEH99	ReFH2-FEH13
Section 3	N	Y	Y
Section 4	N	N	Y
Section 5 & Report R1	N	N	N
Section 6 & Reports R2 & R3	Y	Y	N
Section 7 & Report R4	N	N	N
Section 8 & Report R5	N	N	N
Section 9 & Report R6	N	N	Y
Section 10 & Report R7	Y	Y*	N
Section 11 & Report R8	N	N	N
Section 12 & Report R9	N	N	N
Section 13	N	N	Y

Note: *preliminary assessment only

1.3 Structure of the report

This report has been structured to provide potential users with the main outcomes of the research so that the recommendations can be put into practice immediately. Section 2 outlines the main recommendations for flood and runoff estimation in small catchments and plots, provides a broad summary of the main analyses and presents maps of the new precautionary rainfall, peak runoff and volume estimates. A summary of the evidence supporting the recommendations is provided in Section 3, and in Section 4 several worked examples illustrate how to implement the methods.

Sections 5 to 13 provide more detail about the data and analyses carried out, together with references to the series of technical reports produced during the course of the project. The flood peak data sets developed during the project are described in Section 5, and Section 6 presents the main outcomes of an analysis of the performance of existing methods of flood estimation using these data sets. Details of the main analyses are presented in Sections 7 to 10, focusing on the revision of the QMED catchment descriptor equation for small catchments and the use of donor transfer, the development of an improved pooling procedure, the estimation of design hydrographs and the estimation of plot-scale runoff, respectively. Summaries of other analyses carried out during the project are provided in Sections 11 and 12. Section 13 describes the steps taken to develop a preliminary screening tool for estimating runoff for plot-scale areas. Finally, the conclusions drawn from the research project are set out in Section 14, together with recommendations for practitioners and for further research.

2. Main results and recommendations

2.1 Recommendations

The following recommendations for estimating flood peaks and hydrographs in small catchments (< 25 km^2) and plots (usually < one hectare) in the UK have been made as a result of this research:

2.1.1 QMED estimation

For estimating QMED, the median annual flood, in small ungauged catchments using FEH statistical method, it is recommended that the existing FEH catchment descriptor equation (Equation 1) as published in Kjeldsen and others (2008) is applied.

Equation 1 – FEH catchment descriptor equation

$$\mathrm{QMED} = 8.3062 AREA^{0.8510} 0.1536^{\frac{1000}{SAAR}} FARL^{3.4451} 0.0460^{BFIHOST^2}$$

The standard approach to adjusting the ungauged estimate of QMED by donor transfer, selecting the donor from the whole QMED-suitable dataset using the distance between catchment centroids, continues to be recommended in all catchments including those smaller than 25 km^2. However, it is recommended that only a single donor catchment should be used when the target site is a small catchment. No advantage in selecting the donor in terms of its similarity to the target site in terms of catchment area or average annual rainfall has been identified.

The FEH statistical method and ReFH2-FEH13 performed similarly well in general, and both were better than the other methods tested. However:

- The FEH statistical method may overestimate QMED in small catchments where $\mathrm{URBEXT}_{2000} \geq 0.03$ and SAAR ≥ 800 mm, with overestimation increasing as SAAR increases beyond 1200, so results should be compared to ReFH2 and ReFH2 may be preferred (but see next bullet point)
- ReFH2-FEH13 has a small tendency toward an underestimation bias in urban catchments
- FEH statistical method performed better than ReFH2 in permeable catchments so should be preferred for permeable catchments

2.1.2 Pooling-group selection

A modified method for defining pooling-groups for small and intermediate-sized catchments (≤ 40 km^2) based on hydrological similarity has been developed. The new method defines a similarity distance measure (SDM) using two catchment descriptors as shown in Equation 2.

Equation 2 - Defining pooling-groups for small and intermediate-sized catchments based on hydrological similarity

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

Pooling-groups for small and intermediate-sized target catchments (≤40 km2) should be drawn from the full set of pooling-suitable catchments in the National River Flow Archive (NRFA) Peak Flow data using Equation 2 to determine the most suitable membership. For larger catchments (>40 km2) the existing FEH statistical method (Kjeldsen and others. 2008) should be applied.

For all sizes of target catchment, it is recommended that the derived pooling-groups should be verified. This will include checking for any catchments with different hydrological response (including the effect of lakes and reservoirs), short duration, and questions about data quality. One aspect to consider is where there are significantly different L-moment ratios to others in the pooling-group and considering removal of it only if the difference in L-moments is due to serious hydrological differences between the pooling-group member and the target.

2.1.3 Design hydrograph approach

ReFH2 Hydrograph shape and the FEH recommended storm duration has been verified as being broadly appropriate for most catchment types. It remains difficult to characterise typical hydrograph shape in highly urbanised and/or groundwater dominated small catchments.

The recommendations for seasonal and urban parameter inputs to the ReFH2 design package have been reviewed and the following now apply. These are scale-independent and apply to all catchments (not just small catchments):

- if $URBEXT_{2000} \geq 0.30$ (the catchment is very heavily urbanised), 'Urbanised' results from summer storms with summer initial soil moisture, C_{ini}, should be used (not applying a summer C_{ini} in conjunction with a summer storm will result in significant over-estimation of peak flows and percentage runoff)
- if $0.15 \leq URBEXT_{2000} < 0.3$ (the catchment is moderately urbanised) using 'Urbanised' results in ReFH2 will give a high estimate - winter storms are recommended, unless the catchment is dry (SAAR < 800 mm) and permeable (BFIHOST ≥ 0.65) - the default impervious fraction (IF) of 0.3 should be retained, but the Tp scaling factor should be increased to 1 as there is no evidence for enhanced routing of urban runoff in moderately urbanised catchments
- if $URBEXT_{2000} < 0.15$, winter storms should be used by default

Results of an analysis of hydrograph time-to-peak, Tp, in small catchments and plots led to the following conclusions:

- the lower limit of one hour for Tp should be retained for both catchment and plot-scale application
- for catchments close to 0.5 km^2 in area, the catchment equation (based on FEH hydrological catchment descriptors) should be used to estimate Tp unless unusually high, low or uncertain values of DPLBAR or DPSBAR give a clear justification for

adopting the plot-scale Tp estimate (based on descriptors that do not rely on the digital river network)

2.1.4 Plot-scale runoff rates and volumes

The first phase of this project provided evidence that methods such as IH 124 and ADAS 345 are outdated and inappropriate and their use for plot-scale runoff estimation should be discontinued.

An analysis of a very small set of plot-scale runoff data has provided limited evidence to suggest that FEH methods based on the plot scale (for example, where catchment descriptors have been adjusted) generally produce higher estimates of QMED than methods that scale results from larger catchments. This finding has different implications depending on whether it is runoff at the outlet of the plot or the contribution of the plot to downstream flood risk which is being estimated. The results underline the importance of considering the hydrological characteristics of both plot and downstream catchment.

Since the start of this project, the ReFH2 design package has been released and now provides the option of using plot-scale flow estimation using catchment descriptors that do not rely on a stream network. An evaluation of an early version of ReFH2 within this project concluded that it is broadly appropriate for simulating runoff generation in the example plots.

For estimating greenfield runoff rates and storage volumes, it is recommended that a winter storm and profile should be used in all applications.

Free, open-source data have been used to develop a set of estimated greenfield runoff rates (l/s/ha) for return periods of 12 months, 2, 30 and 100 years across England and Wales. In addition, estimates of runoff rates and volumes are provided for the 100-year event of 6-hour duration for calculating long-term storage. Although every effort was made to make the results conservative, that is to underestimate greenfield runoff rates, the estimates are generalised and not always precautionary as they are subject to considerable uncertainty.

Maps of results are presented in Section 13 and it is intended to make them freely available via GOV.UK. See Appendix B for further details.

2.1.5 High intensity, short duration rainfall

The results of an analysis of rainfall frequency based on rainfall observations for durations ranging from one to 120 minutes at 19 rain gauges in England and Wales showed the FEH13, FEH99 and FSR depth-duration-frequency models give reliable results for such short durations at return periods of less than 10 years, even though little or no sub-hourly data were used in their calibration.

Work on extrapolating the FEH13 rainfall model to sub-hourly durations was carried out outside this project. The ratio of x-minute to 60-minute estimates from the FSR at each 1 km grid point was used to derive sets of scaling factors which were applied to the FEH13 60-minute values for sub-hourly durations down to five 5 minutes. The resulting FEH13 values for durations from five to 60 minutes were disseminated via the FEH Web Service.

2.1.6 Important note on generalised methods

These recommendations are generally applicable for the whole of UK. However, in line with other guidance on flood estimation, practitioners should always seek as much relevant information on local circumstances as possible and should always exercise judgement in the application of generalised methods.

Further advice is provided in:

- the outputs of the Environment Agency’s project ‘Making better use of local data in flood frequency estimation’ (Environment Agency 2017)
- the Environment Agency's Flood Estimation Guidelines, LIT 11832 (Environment Agency, 2022) available by request from: FloodHydrology@environment-agency.gov.uk
- Natural Resources Wales 'Flood Estimation: Technical Guidance Note GN008' available by request from: https://cyfoethnaturiolcymru.gov.uk/about-us/contact-us

2.2 Outline of the research

The following paragraphs summarise the main parts of the analysis carried out during the project. Further details are provided in Sections 5-14 of this report and in the series of project reports listed in Section 1.2.

2.2.1 Observed flow data (Section 5)

A new set of peak flow data for 217 small catchments, including those with areas up to approximately 40 km^2, were developed for this project. Data are mostly in the form of annual maxima peak flows, although for several gauges only QMED values, the median annual or 2-year flood, are available. Some parts of the UK such as Scotland and the West Midlands are not well represented in the data set, mainly due to issues with data quality. Urban catchments are not particularly well represented in the data set, but average permeability and annual rainfall characteristics are similar to average values across the whole NRFA peak flow data set.

During the analysis, the main data set was subdivided into ‘high-quality’ and ‘extended’ subsets as well as further subsets defined based on area, permeability and the extent of urbanisation.

2.2.2 Baseline assessment (Section 6)

The first part of the analysis was a baseline assessment to consider the performance of existing FEH flood estimation methods and the QMED equation developed by MacDonald and Fraser (2013) using the project data set, carrying out separate analyses for rural and urban catchments. The ReFH2 method was applied together with original FEH99 design storm inputs (Faulkner 1999), as it was carried out before the development of ReFH2.2 (Wallingford HydroSolutions 2016a), a modification in which the equations for parameter values and initial conditions were reoptimised for FEH13 rainfall depths. However, additional assessment of the then current ReFH2.2 with FEH13 rainfalls took place during later stages of the project, including development of the revised QMED equation for small catchments (Section 6), recommendations for design hydrograph estimation (Section 8), development of the free greenfield plot-scale peak flow rate and volume screening data (Section 13), and assessment of evidence for project recommendations (Section 3).

The baseline assessment showed that there was little distinction between the 'high quality' and 'extended' data sets in terms of the performance of the FEH methods. It concluded that there is no tendency for any method to over or underestimate QMED with respect to catchment area. For QMED estimation, the strongest performance overall in rural catchments was given by ReFH2-FEH99. The FEH statistical method was found to outperform MacDonald and Fraser's method and to have a particular advantage in more permeable catchments. In urban catchments, error in QMED estimates from the FEH methods was not found to be related to urban extent, except in the most heavily urbanised case.

For return periods up to 500 years, the ReFH2-FEH99 method gave the smallest residuals, although all FEH methods were generally found to apply equally in estimating Q100 as they are for QMED. The assessment was restricted to considering the set of as-rural small catchments classified as suitable for pooling procedures.

The baseline assessment concluded that there was scope for improving FEH methods in small, particularly urban catchments, and recommended exploring QMED estimation, pooling procedures, the form of design hydrographs and clarifying the recommended design inputs to the ReFH package.

2.2.3 QMED estimation in small catchments (Section 7)

The project flow peak data set was analysed to consider 3 general options for reducing uncertainty in estimating the index flood in small catchments:

Option 1: Recalibrating the FEH catchment descriptor equation using a data set of small catchments only to provide a 'retuned' QMED equation (Equation 20). The retuned equation was developed using catchments of up to 25 km^2 in area. For this reason, a linear interpolation method was proposed to allow QMED estimation for catchments between 25 and 40 km^2 using both the small catchment retuned equation and the all-catchment (existing FEH) equation. In this report, this method for intermediate sized catchments is referred to as the 'composite method'.

Option 2: Developing a new QMED regression equation, based on other catchment descriptors that are found to explain more variation in the observed QMED in small catchments.

Option 3: Developing a new QMED equation based on regression as above, but with consideration given to using flow statistics in combination with catchment descriptors. These flow statistics require some gauging but can be estimated using equipment that is accurate at flows much lower than QMED.

Both options 1 and 2 were judged to offer improvements in terms of uncertainty in QMED, but the improvement offered by option 2 over option 1 was considered too small to justify a complete overhaul of the model structure. The gauged flow equation (option 3) was found to give the best model fit to observed median annual flows. However, the smaller number of catchments for which flow statistics were obtained means that this regression equation cannot be generalised safely to all small catchments.

Subsequent work to evaluate the performance of the retuned QMED equation concluded that there was little evidence to support using it rather than the existing FEH QMED equation of Kjeldsen and others (2008) (see Section 3).

The current FEH guidance on donor adjustment was reviewed using the small catchment data set and new guidance was developed.

2.2.4 Estimating the T-year flood in small catchments (Section 8)

The project has developed a new procedure for selecting pooling-groups for small catchments. The procedure was developed separately for each subset of catchments (under/over 25 km^2 and suitable for pooling/QMED estimation/not known), while the full set of 191 catchments with available annual maximum flow data (up to 40.9 km^2, not necessarily suitable for pooling) was used for verification. A new similarity distance measure (SDM), with less emphasis on catchment area, was developed to assess the similarity between the catchment of interest and potential pooling-group members, while all other parts of the pooling procedure (weighting equations, target record length, default distribution) were left unchanged.

2.2.5 Recommendations for estimating design hydrographs (Section 9)

Design flood hydrographs provide important information for flood studies and complement statistical methods of estimating catchment peak flows. Hydrograph shape gives an indication of the full runoff response to an extreme rainfall event, which can be particularly important in reservoir storage and floodplain modelling. During the project, three separate analyses were carried out relating to estimating design hydrographs in small catchments and plots.

Firstly, the current recommendations for seasonal design inputs to the ReFH2 method, which are linked to the extent of catchment urbanisation, were reviewed. The implications of the analysis have been condensed into a set of rules for selecting when summer storms should be used within ReFH2 (see Section 9). The review suggests that the current summer storm profile is too peaked and recommends that estimating storm profiles requires further research across the full range of catchment scales.

Secondly, a review of the evidence for imposing a lower limit of catchment time-to-peak (Tp) of one hour in small catchments and plots was carried out. The results indicate that in small catchments (between 0.5 and 25 km^2) the lower Tp limit of one hour should be retained, and that it is marginal as to whether the catchment Tp or plot-scale Tp equation should be used. In the case of estimating plot-scale runoff, the results suggest that it is appropriate to limit Tp to one hour as this will provide a conservative estimate of the allowable rate of discharge from a development site.

The final analysis compared two different approaches to estimating hydrograph shapes for design flood estimation: the ReFH2 rainfall-runoff method and the empirical median hydrograph (EMH) method, outlined by Archer and others, 2000. It was concluded that, within the limitations of sample size and the limitations of both methods, it is reasonable to conclude that the hydrograph shape predicted by ReFH2 is generally consistent with the shape of observed events, particularly in rural catchments.

2.2.6 Estimating plot-scale runoff (Section 10)

Early in the project a study of the suitability of existing FEH methods for plot-scale applications was carried out. This started from the hypothesis that dominant hydrological processes at hillslope or plot scale may be very different from those at a larger scale, even if the larger scale is still only a few square kilometres. Analysis of three small plots (0.44 to 1.03 ha) provided some limited evidence that methods based on the plot scale (that is, where catchment descriptors have been adjusted or QMED estimated directly from plot peak-over-threshold data) may produce higher estimates of QMED than methods based on scaling results from larger catchments.

2.2.7 Using local data in small catchment flood estimation (Section 11)

A study of the relationships between catchment vegetation, land management and flood runoff was carried out to explore their potential for improving small catchment flood estimation. A review of the literature on hydrologically monitored catchments revealed that it is difficult to generalise about the effects of vegetation and land management at the catchment scale. Moreover, there are few tools available to allow practitioners to quantify the likely effects of different types of vegetation and land use on the flood frequency curve. Hydrologists are therefore recommended to seek local data where possible and apply their judgement when faced with unusual catchments.

2.2.8 Short duration rainfall depth-duration-frequency (Section 12)

In the early stages of the project, a depth-duration-frequency (DDF) analysis of short duration rainfall data for 19 rain gauges in England and Wales was carried out. A modified version of the generalised extreme value (GEV) distribution was used to model the annual and seasonal maxima for a range of durations at each site, giving a good fit to the observed data and performing well for the shorter return periods for which reliable estimates of rainfall frequency can be obtained from observations. Comparisons with the results from standard national DDF models showed that even though the existing methods used little or no sub-hourly data in their calibration, they gave fairly reliable estimates of rainfall overall, with low bias and moderate scatter when compared to gauged estimates of the 2-, 5- and 10-year rainfalls for different durations.

2.2.9 Free screening tool for estimating greenfield runoff rates and volumes (Section 13)

Gridded data sets of plot-scale estimates of peak flow rates and volumes in England and Wales have been compiled using freely available data. The 1 km-resolution peak flow rate estimates cover return periods of one, 2, 30 and 100 years which are relevant to drainage design, as well as the 6-hour duration, 100-year return period event. To estimate runoff volume, a second more conservative, yet more uncertain, model was generated.

The freely available rainfall and soil data were used to fit regression models that aim to give more conservative values (low peak greenfield flow rate and runoff volume). To achieve this, a free alternative to the standard baseflow index was generated using open-source European soil data. The models appear to perform better than IH124, but not as well as those generated from ReFH2 with FEH13 rainfalls.

Conservative estimates cannot be guaranteed for any individual site, so this tool is seen as a screening mechanism only and should also be accompanied by using the latest ReFH-FEH DDF design package. If a more conservative estimate is required, both the free methods and the latest ReFH-FEH DDF design package should be applied, and the more conservative value taken.

2.2.10 Testing the recommendations (Section 3)

The recommendations developed during the project, summarised in Sections 2.2.1 to 2.2.9, were tested against each other at the end of the project for return periods of 2, 100 and 1,000 years. The target values for the 2-year return period were the median of at-site annual maxima, while enhanced single-site analysis provided the target values for longer return periods.

At QMED, this test revealed that the new small-catchment QMED equation tended to consistently underestimate. Therefore, the recommendation was made to continue using the existing all-catchment QMED equation. Additionally, ReFH2-FEH13, with the recommendations identified during the project, was found to be less biased and slightly less uncertain than ReFH2-FEH99. At return periods of 100 and 1,000 years, the new small-catchment pooling methodology was found to offer lower uncertainty than the existing procedure, leading to the new procedure being recommended. ReFH2-FEH13 was found to give more consistent results than ReFH2-FEH99, in terms of bias and factorial standard error (fse), as a function of catchment urbanisation and rainfall return period.

2.3 Choice of methods

Table 2 summarises the FEH methods for flood estimation, giving some detail on their application and limits on their applicability. Older methods (for example, ReFH1, ReFH2 with FEH99) are not included in the table These older methods should be considered generally not applicable for flood estimation.

Table 2 - Summary of recommended methods for flood estimation

Method	Return period	Notes
At-site analysis	Up to half the number of valid at-site annual maxima	Best method if confidence in gauging accuracy is sufficient.
Enhanced single-site analysis	Up to 1,000 years	Next best after at-site analysis. Suitable for longer return periods than at-site.
QMED linking equation	1-in-2 year (QMED) only	Generally superior to ungauged methods (FEH statistical and ReFH2) but inferior to at-site analysis for estimating QMED.
FEH statistical method	Up to 1,000 years	Use QMED linking equation or original QMED equation. Use new small-catchment similarity distance measure (SDM). Do not limit potential pooling-group members by catchment area or any other catchment property. Review the suggested pooling-group for obvious hydrological differences.

Method	Return period	Notes
ReFH2	Up to 1,000 years	FEH13 rainfall should be used instead of FEH99 or FSR rainfall . Standard (not plot-scale) equations should be used whenever possible, regardless of plot/catchments size, unless DPLBAR or DPSBAR is outlying (very high or very low). Winter storms, profiles and conditions should be used unless $URBEXT_{2000} \geq 0.3$ or $URBEXT_{2000} \geq 0.15$ and $BFIHOST \geq 0.65$ and $SAAR < 800$ mm. In this later case, Tp should be increased to1 as there is no evidence of enhanced routing of urban runoff in moderately urbanised catchments.
Free screening tool for estimating greenfield runoff rates and volumes	1-in-12 month, 1-in-2 year, 1-in-30 year and 1-in-100 year only	Results have high uncertainty and are biased towards underestimating greenfield peak flow and runoff volume. Use for screening only, as a replacement for IH124.

3. Evidence for recommended methods in small catchments

This section provides evidence to support the recommendations outlined in Section 2. During the project, three new QMED estimation equations based on catchment descriptors and flow regime statistics were developed using the small catchment data set described in Section 4. In addition, a new pooling procedure for small catchments was also developed. At the same time, but outside this project, developments were made to the ReFH2 procedures for all catchments, and the updated design package has been included in this comparison of method performance in small catchments.

3.1 Introduction

The performance of the existing all-catchment statistical FEH method and the new methods developed for small catchments during this project were compared to provide the evidence that led to the recommendations set out in Section 2. The application of the ‘retuned’ small catchment QMED equation used the composite method for catchments between 25 and 40.9 km^2 (see Section 2.2.3 and project report R4). The benefits of donor transfer (the correction of a catchment descriptor-derived QMED estimate using data at a nearby gauged site) were not considered when cross-comparing methods. Urban adjustments were applied.

Two variants of the ReFH2 design package were also included in this comparison: the ReFH2-FEH13 package, which uses the FEH13 rainfall depth-duration-frequency (DDF) model (Stewart and others, 2013) to provide design storm inputs, and ReFH2-FEH99, which relies on the original FEH99 DDF model. Further details of the design packages are given in Section 9. The version of the ReFH2-FEH13 package applied here includes the recommendations made in Section 9 about using summer storms for very heavily urbanised catchments and retaining the lower limit of one hour for hydrograph time-to-peak, Tp. All results were generated using the catchment-scale design equations.

3.2 Data

The baseline assessment of methods (see Section 6) showed that there was little distinction between the ‘high-quality’ and ‘extended’ data sets in terms of how the FEH methods perform. For this reason, the two data sets were combined for the cross-comparison exercise. From the ‘extended’ dataset of 217 small and intermediate-sized catchments, 10 were excluded as their values of the FARL catchment descriptor, indicating a high degree of flood attenuation due to reservoirs and lakes, made applying ReFH2 inappropriate.

3.3 Method performance at QMED

Figure 1 presents residuals in ln(QMED) estimates obtained using the new composite small catchment method (SC) and the two ReFH2 methods (REFH2-FEH99 and ReFH2-FEH13), against residuals in ln(QMED) obtained from the current FEH all-catchment QMED equation ('Current').

Residuals are calculated according to: $\ln(QMED_{mod}) - \ln(QMED_{obs})$.

$QMED_{obs}$ is the median of observed AMAX at a station and $QMED_{mod}$ is modelled QMED at the same station, using any of the methods mentioned in the previous paragraph.

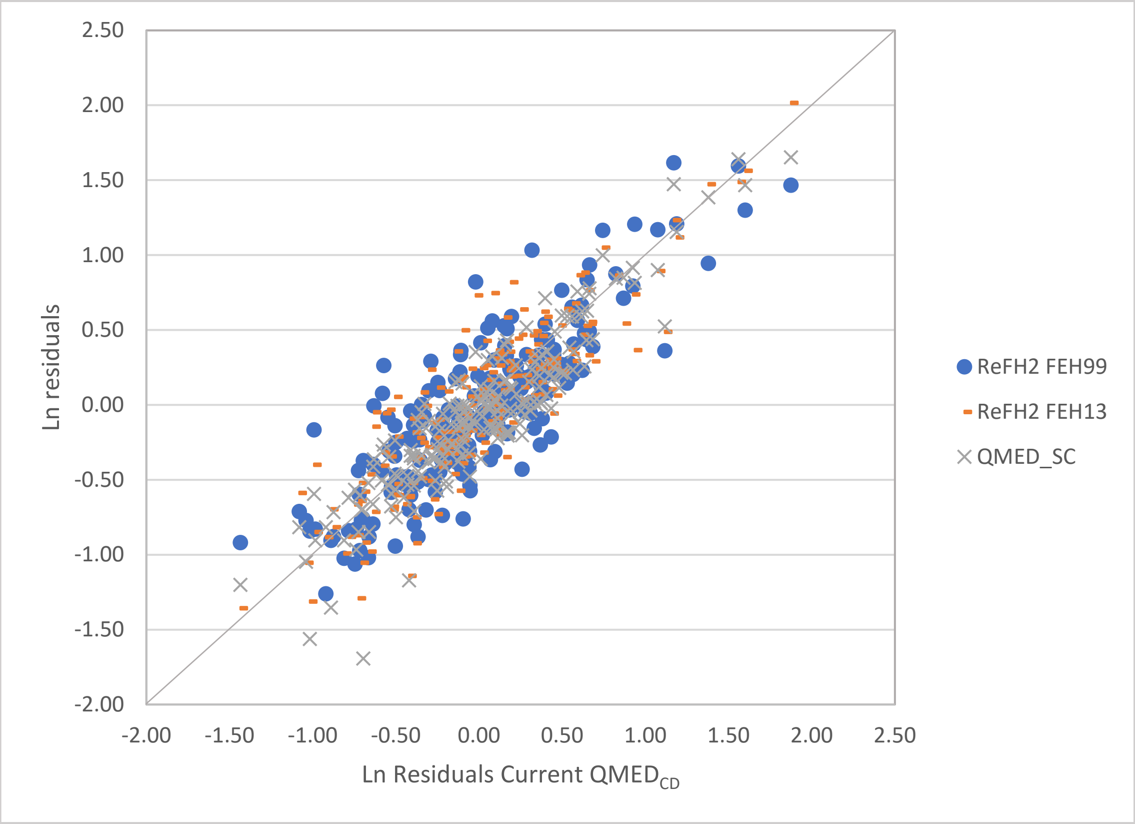

Figure 1 - Comparison of model residuals with model residuals for the existing FEH QMED equation

The x-axis of Figure 1 plots the Ln Residuals Current $QMED_{CD}$ (from -2.00 to 2.50).The y-axis show the Ln residuals from -2.00 to 2.50. The legend shows:

- ReFH2 FEH99 (blue dot)
- ReFH2 FEH13 (red dash)
- QMED_SC (grey cross)

The following observations are made:

- the residuals for all methods are very strongly correlated; that means that in a catchment where one method performs poorly, all methods tend to perform poorly - this would suggest either common errors in the assumption of contributing area, errors in hydrometry, or that all methods and/or catchment descriptor data are unable to reflect catchment-specific features such as complex urban influences or catchments with very complex soils and geology
- the range of differences in residuals for methods within individual catchments are generally very much smaller than the range of differences between catchments, reinforcing the first point
- the new composite statistical QMED method is more strongly correlated with the existing FEH statistical method except in some of the catchments with the largest negative residuals (indicating underestimation) - this is to be generally expected as the statistical methods are the same for the larger catchments in the data set
- the ReFH2-FEH13 residuals are generally more strongly correlated with the existing FEH statistical method estimates than the ReFH2-FEH99 residuals, noting that both ReFH2 methods are independent of the FEH QMED catchment descriptor equation

Outlier catchments, with average residuals in ln(QMED) across all methods outside the range ±0.69, were selected for further analysis. Residuals for ln(QMED) outside ±0.69 correspond to estimates that are less than half or more than double the observed value. For half of outliers, there was enough evidence to suggest that the contributing areas were significantly smaller than the topographic catchment areas, and they were excluded from further analysis. For the remaining outliers, the measurement of high flows was of concern and, in one case, the flow regime was dominated by a reservoir.

Histograms of the residuals in ln(QMED) for each method (with outliers removed) are presented in Figure 2. These are summarised as overall bias and factorial standard error (fse) in, which considers three categories: all catchments, predominantly rural catchments, and significantly urbanised catchments.

Equation 3 - Overall bias across n catchments

$$\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{QMED}_{mod,i} \;/\; \mathrm{QMED}_{obs,i}\right)$$

Equation 4 – Calculating factorial standard error (fse)

$$\exp\sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}\left(\ln\left(\mathrm{QMED}_{mod,i}\right) - \ln\left(\mathrm{QMED}_{obs,i}\right)\right)^{2}\right)}$$

From the bias calculation, a value of one is unbiased. Bias values below one indicates underestimation and bias values above one indicates overestimation.

Table 3 details error statistics for all catchments, and for a subset of catchments that either essentially rural predominantly rural (URBEXT2000 < 0.03) or significantly urbanised catchments (URBEXT2000 ≥ 0.03).

Table 3 - Error statistics summarising model error at QMED over all catchments, predominantly rural (URBEXT2000 < 0.03) and significantly urbanised catchments (URBEXT2000 ≥ 0.03)

Catchment types	Statistic	Statistical pooled (existing FEH method)	Statistical pooled (small catchment method)	ReFH2 (with FEH13 rainfalls)	ReFH2 (with FEH99 rainfalls)
All catchments	Bias	0.99	0.93	1.00	0.96
All catchments	fse	1.53	1.51	1.55	1.56
Rural catchments	Bias	1.00	0.92	1.00	0.91
Rural catchments	fse	1.54	1.52	1.55	1.55
Urban catchments	Bias	0.91	0.96	0.95	1.22
Urban catchments	fse	1.49	1.63	1.47	1.63

Note: fse = factorial standard error

The x-axis of Figure 2 plots the log residual (from -1.5 to 1.3). The y-axis shows the frequency (from 0-45). The legend shows:

- SC statistical (blue)
- ReFH2 FEH13 (orange)
- ReFH2 FEH99 (grey)
- current statistical (yellow)

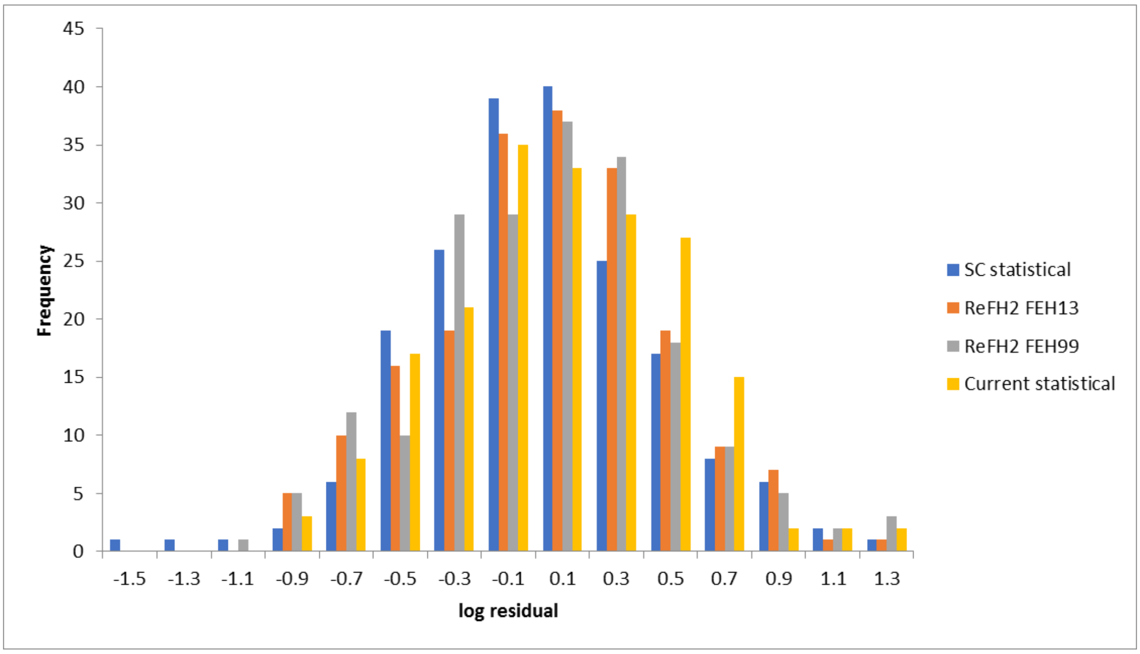

Figure 2 - Histogram of residuals for ln(QMED) estimation

The following observations can be drawn from the results in Table 3 and Figure 2 for the two statistical methods:

- the small catchment methods overall and in rural catchments result in a small reduction in fse compared with both the existing statistical and ReFH2 methods - in urban catchments, fse is larger than for both the existing statistical method and the ReFH2-FEH13 design package
- the new small catchment method is biased towards underestimation in both all and rural catchments compared with the existing methods, which are essentially unbiased across all catchments and the rural catchments subset
- in the urban catchments, the small catchment statistical method has the smallest bias of any method (although marginally less than the ReFH2-FEH13 package) and the existing FEH statistical method has the greatest bias - however, the fse is the joint largest with ReFH2-FEH99

For the two ReFH2 design packages the following patterns can be identified:

- over all catchments, the two ReFH2 design packages give very comparable results - however, the FEH99 design package is biased towards underestimation, whereas the FEH13 package is unbiased
- the FEH99 package is biased towards underestimation in rural catchments and towards overestimation in urban catchments - the FEH13 package has a small tendency toward an underestimation bias in urban catchments
- the fse values are very similar in both all and rural catchments for both design packages - in urban catchments, the fse values are higher, slightly so for the FEH13 package but more so for FEH99

It is reasonable to conclude that ReFH2-FEH13 and the existing FEH statistical method have the overall best performance when considering the magnitudes of the biases in estimates and the magnitudes of the standard error. In urban catchments, the ReFH2-FEH13 design package is the best performing method with the best compromise between estimation bias and fse.

Figures 3, 4, 5 and 6 present the relationships between model residuals and catchment area for the statistical and ReFH methods respectively. The x-axes plot the area from 0-45 km^2. The y-axes show the ln residuals from -2 to 2. The legends show:

- SAAR<800mm BFIHOST<0.65 (blue cross)
- SAAR>800mm BFIHOST<0.65 (black circle)
- BFIHOST>0.65 (green asterisk)

These graphs demonstrate that there is no clear dependency on catchment scale for any of the methods.

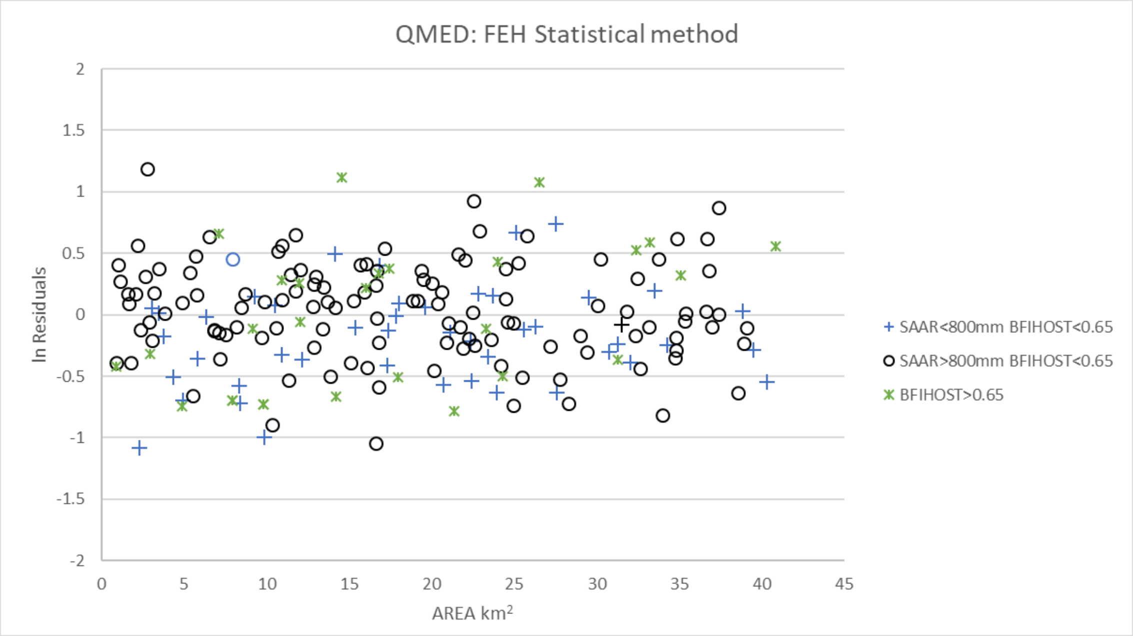

Figure 3 - Relationships between model residuals and catchment area for the FEH statistical method

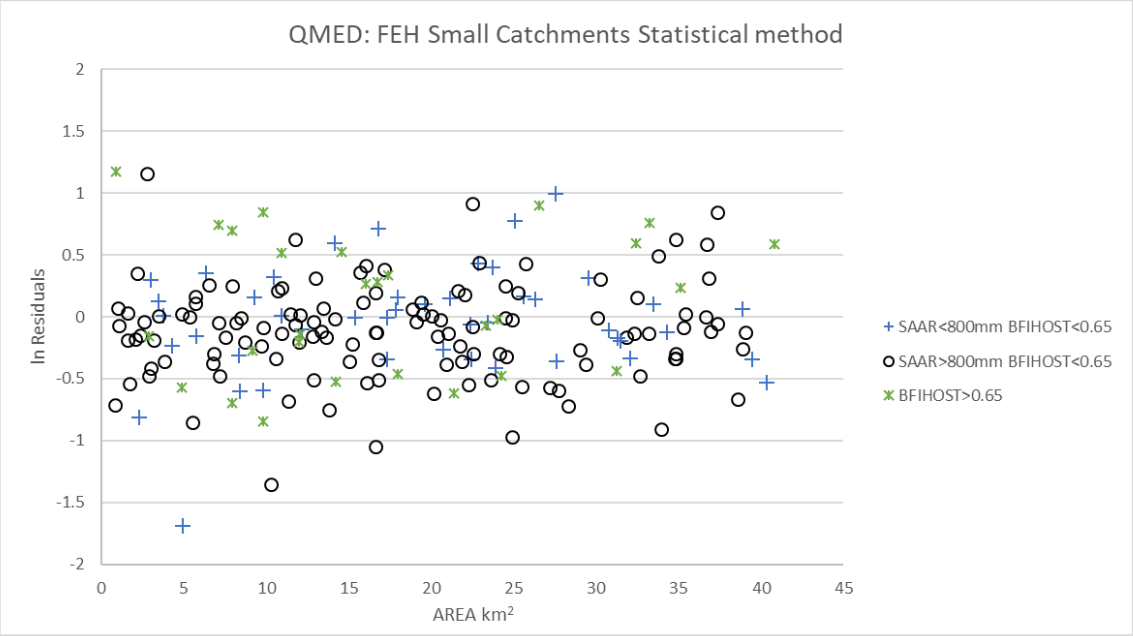

Figure 4 - Relationships between model residuals and catchment area for the FEH small catchments statistical method

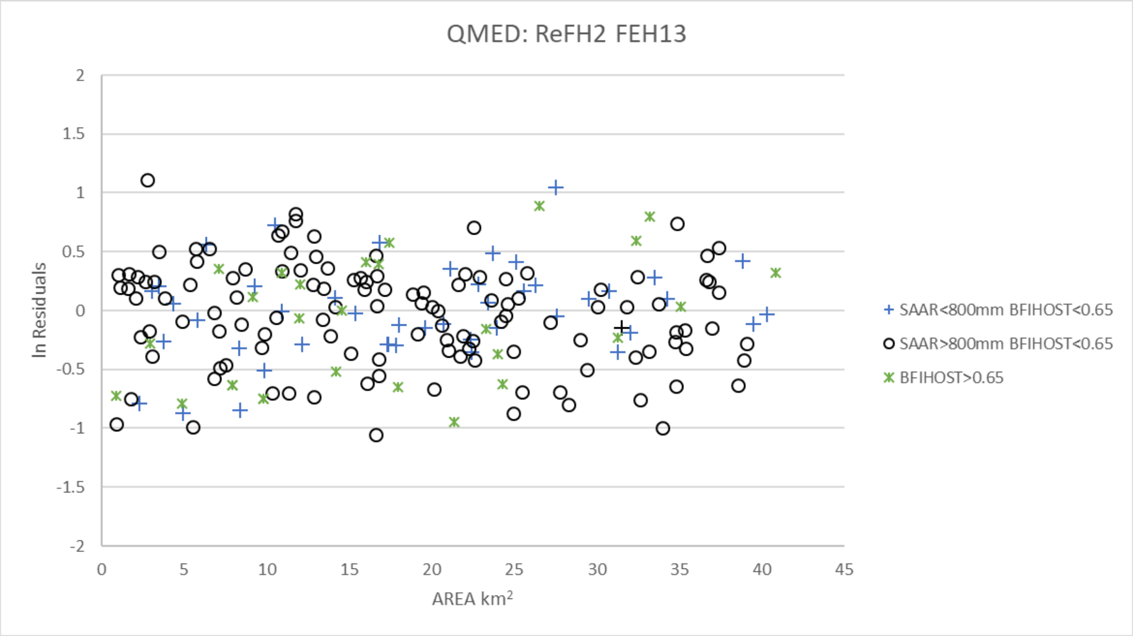

Figure 5 - Relationships between model residuals and catchment area for the ReFH2 FEH13 method

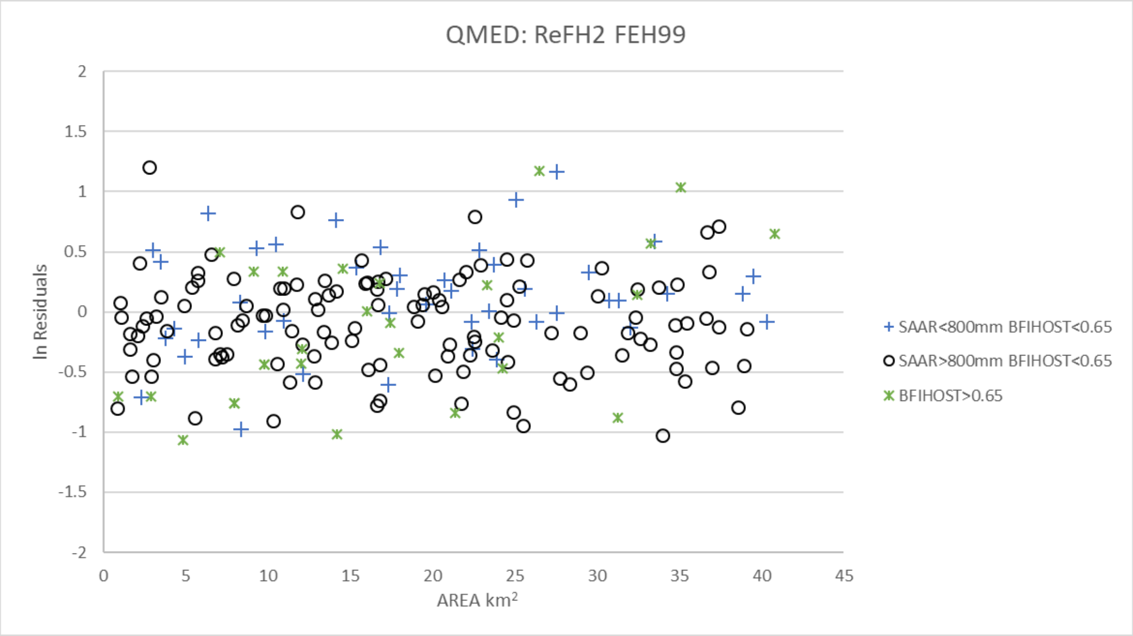

Figure 6 - Relationships between model residuals and catchment area for the ReFH2 FEH99 method

The catchments in Figures 3, 4, 5 and 6 are classified based on SAAR (standard period average annual rainfall in mm) and BFIHOST (baseflow index from the HOST soil classification). Less permeable catchments (BFIHOST < 0.65) were subdivided into high (SAAR ≥ 800) and low (SAAR < 800) rainfall classes; more permeable catchments were not subdivided as there were very few with high SAAR.

These graphs demonstrate that there is no overall clear dependency of the residuals on catchment scale for any of the methods, and no clear dependency on catchment wetness or permeability.

However, it is important not to overemphasise the interpretation of these results as the data set is a small subset of UK catchments (although large in the context of previous studies).

3.4 Comparisons of methods for longer return period events

The current FEH enhanced single-site method was used as the basis for comparing how methods perform at longer return periods. Therefore, the baseline estimates are modelled using a generalised logistic distribution, fitted to L-moments that are averaged from a flexible region of stations selected via catchment descriptors (see Equation 25), although the at-site L-CV is given a higher weight than in an ordinary FEH pooled analysis. Therefore, the bias and factorial standard error statistics must be interpreted as ‘differences’ between tested methods rather than ‘errors’. When testing the existing FEH pooling procedure and revised small catchments procedure, the at-site AMAX data were excluded from the pool.

Histograms of the differences in ln(Q100) for each method are presented in Figure 7. The x-axis plots the log differences (from -3.25 to 1.25). The y-axis shows the frequency (from 0-35). The legend shows:

- SC statistical (blue)
- ReFH2 FEH13 (orange)
- ReFH2 FEH99 (grey)
- current statistical (yellow)

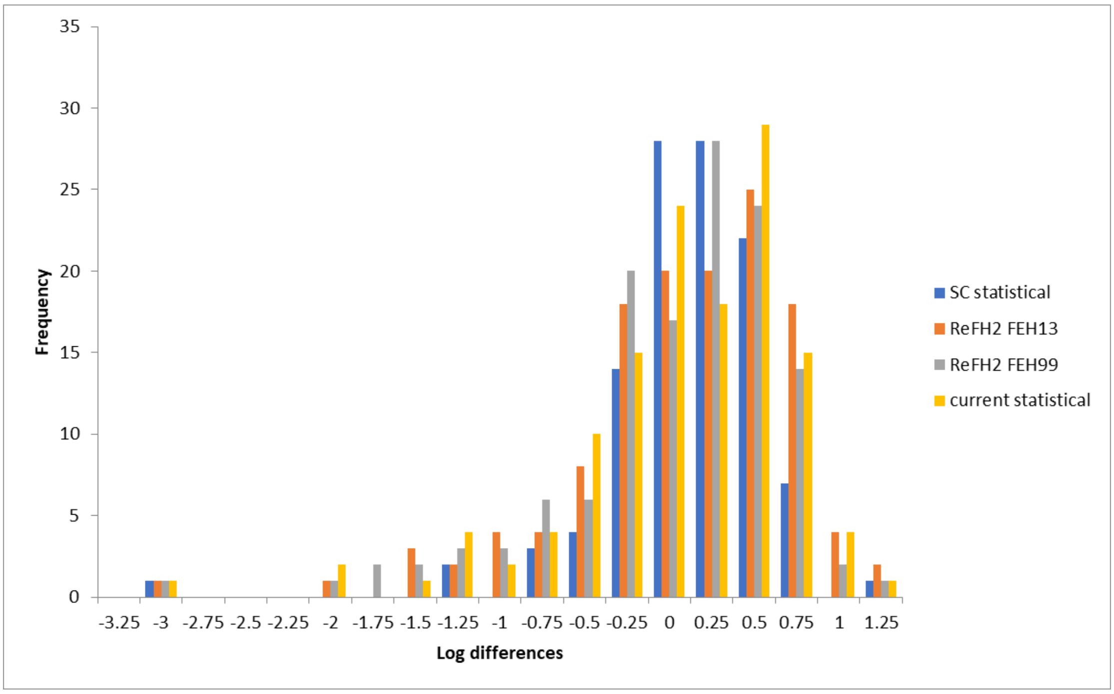

Figure 7 - Histogram of differences between the current enhanced single site estimates for ln(Q100) and the corresponding ReFH2 methods, current pooled statistical methods and new small catchment statistical method estimates

Figure 7 shows several catchments in which the differences between all tested methods and the enhanced single-site method are very large. The differences are a direct consequence of the at-site data and the weight given to these data in enhanced single-site analysis, as the only difference between the enhanced single-site benchmark and one of the tested methods (existing FEH pooling method) is the use of at-site AMAX in the benchmark method. The 10 catchments with the overall largest average difference relative to all methods were further inspected (for example, for erroneous contributing area) and all were omitted from the remaining analyses.

The differences in ln(Q100) for all methods are summarised as overall bias and factorial standard error (fse) in Tables 4 and 5, which considers separately all catchments, predominantly rural catchments and significantly urbanised catchments.

Table 4 - Error statistics for the statistical pooled method against enhanced single-site analysis at Q100 and Q1000, over: all catchments; predominantly rural catchments; significantly urbanised catchments

Catchment types (and count)	Statistic	Statistical pooled (existing FEH) – Q100	Statistical pooled (existing FEH) – Q1000	Statistical pooled (small catchment) – Q100	Statistical pooled (small catchment) – Q1000
All (120)	Bias	0.99	1.01	0.93	0.95
All (120)	fse	1.61	1.70	1.58	1.67
Rural (100)	Bias	1.00	1.03	0.93	0.93
Rural (100)	fse	1.64	1.74	1.57	1.67
Urban (20)	Bias	0.93	0.93	0.98	1.07
Urban (20)	fse	1.44	1.45	1.60	1.63

Table 5 - Error statistics for the ReFH2 against enhanced single-site analysis at Q100 and Q1000, over: all catchments; predominantly rural catchments; significantly urbanised catchments

Catchment types (and count)	Statistic	ReFH2 (FEH13) – Q100	ReFH2 (FEH13) – Q1000	ReFH2 (FEH99) – Q100	ReFH2 (FEH99) – Q1000
All (120)	Bias	1.00	1.10	0.93	0.97
All (120)	fse	1.69	1.77	1.67	1.81
Rural (100)	Bias	0.98	1.08	0.86	0.87
Rural (100)	fse	1.70	1.78	1.69	1.80
Urban (20)	Bias	1.01	1.18	1.40	1.64
Urban (20)	fse	1.53	1.67	1.58	1.85

It must be recognised that that the comparison is with the enhanced single-site estimates (that is, the results from an alternative method rather than directly from observations). It is also noted that these results are drawn from a smaller data set than the comparison of QMED estimates, as not all stations had a full AMAX record, which is required for enhanced single-site analysis. Despite this, the general patterns for the estimates of Q100 reflect those observed for QMED, albeit with larger fse values. This would suggest that the propagation of errors from modelled QMED is having an effect.

The ReFH2-FEH13 estimates of the Q1000 are, on average, higher than the enhanced single-site estimates and the existing FEH and new small catchment pooled estimates. This relationship has been observed in earlier comparisons across all catchments held on the NRFA peak flow database (Wallingford HydroSolutions 2016a). It is a commonly held view among practitioners that the FEH statistical methods underestimate very rare events.

It is inherent that the current pooling procedures will be more strongly correlated with the enhanced single-site estimates, since there will be a large common subset of pooling-group members for both methods. This is not necessarily the case for the new small catchment procedure, so it is surprising that while the new procedures are more biased with respect to the enhanced single-site estimates, their fse values are lower.

Figures 8, 9, 10 and 11 present the relationships between model residuals and catchment area for the statistical methods and ReFH2 respectively for the 100-year return period. The catchments were again classified using SAAR and BFIHOST following the same approach as in the assessment of QMED estimates. The x-axes on the scatter graphs plot the area (from 0-45 km^2). The y-axes show the ln residuals (-2 to 2). The three items in the legend show:

- SAAR<800mm BFIHOST<0.65 (blue cross)
- SAAR>800mm BFIHOST<0.65 (black circle)
- BFIHOST>0.65 (green asterisk)

For catchments larger than 25 km^2, there is little evidence of bias and similar levels of unexplained variance between methods. In permeable catchments, there is a tendency for all methods to give lower estimates than the enhanced single-site statistical method. This is more marked for the two ReFH methods and the existing FEH statistical method, though noting that there are very few small permeable catchments in the data set. In low rainfall, low permeability catchments, there is a tendency for all methods to give lower estimates than the enhanced single-site methods. This is more marked for the two statistical methods.

Below a catchment area of 25 km^2, there is more variation in the ReFH2-FEH13 estimates in the high rainfall, low BFI (Baseflow Index) class. The existing FEH statistical method corresponds most closely to the enhanced single-site estimates (these methods are the least independent). In contrast, the new small catchment statistical estimates generally tend to be lower than those from the existing FEH enhanced single-site method.

As noted for the analysis of QMED estimates, it is important not to give too much weight to the interpretation of these results as the data set, although large in the context of previous studies, is still a small subset of UK catchments of this scale.

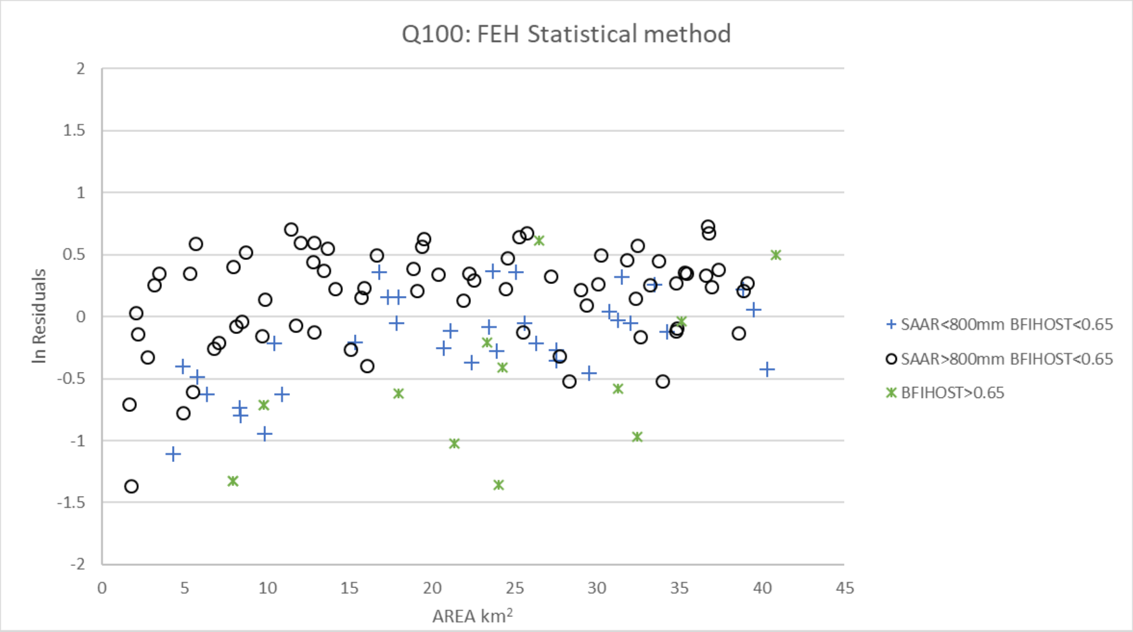

Figure 8 - Relationships between model residuals and catchment area for the FEH statistical method

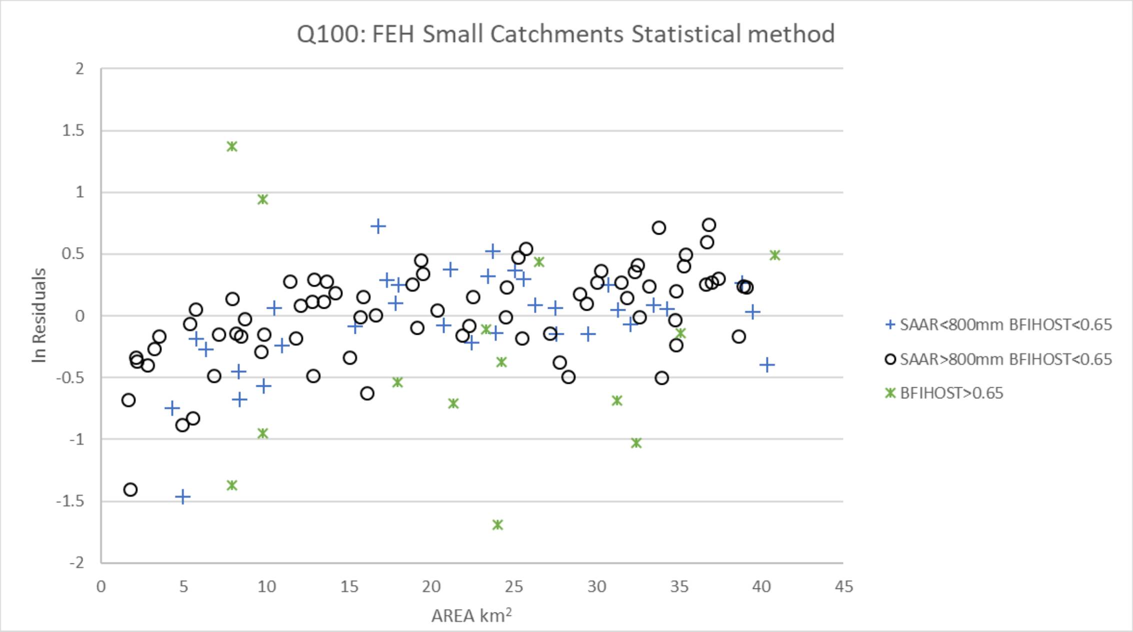

Figure 9 - Relationships between model residuals and catchment area for the FEH small catchments statistical method

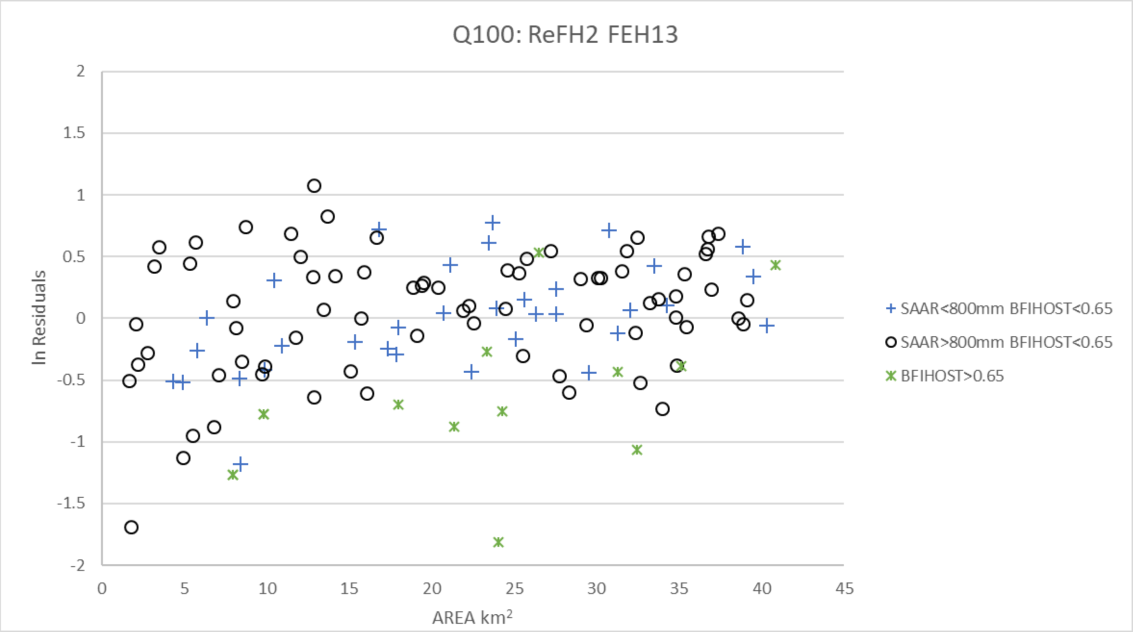

Figure 10 - Relationships between model residuals and catchment area for the ReFH2 FEH13 method

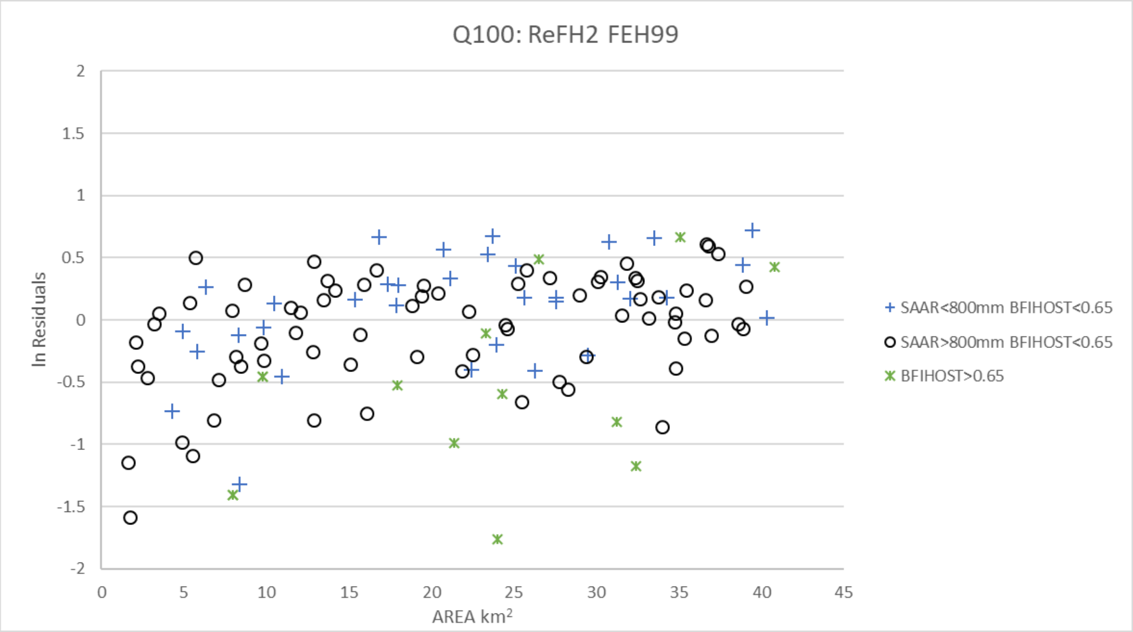

Figure 11 - Relationships between model residuals and catchment area for the ReFH2 FEH99 method

4. Worked examples

This section presents three worked examples to demonstrate flood estimation using the existing FEH methods, the new recommendations for small catchment flood peak estimation, and to show how they differ, focusing on one rural catchment, one urban catchment and one plot (≤ 0.5 km^2).

In all cases, methods will be applied to estimate the 1-in-12-month, 1-in-2-year, 1-in-30-year and 1-in-100-year flood events, considering peak flow and runoff volume for the recommended rainfall duration. The 6-hour, 100-year event will also be considered, as this is used for drainage design of greenfield developments.

As this chapter considers only three case studies separately, no conclusions can or should be drawn about the relative effectiveness of each method in each case. Evidence for the relative effectiveness of the new and existing flood estimation methods should be drawn from large-scale studies reported in Sections 5-14 and the large- scale verification reported in Section 3.

General advice to help analysts is available in the Environment Agency's Flood Estimation Guidelines LIT 11832, Environment Agency (2022).

Important information

The term '1-in-12-month event' refers to a return period on the peaks-over-threshold (POT) scale. This scale considers the average amount of time between all events exceeding the threshold. Conversely, FEH methods evaluate return periods on the annual maximum (AMAX) scale. This scale considers the average number of complete water years between events exceeding the threshold, where each year is counted once as 'exceeding the threshold' or not. Therefore, return period on the AMAX scale can never be one or less. Return periods can be converted between the POT and AMAX scales using Langbein's formula shown in Equation 5 (Langbein, 1949).

Equation 5 – Converting return periods between the POT and AMAX scales

$$T_{AMAX} = \frac{1}{1 - e^{\left(\frac{-1}{T_{POT}}\right)}}$$

Therefore, the 1-in-12-month flood becomes a 1-in-1.58-year flood on the AMAX scale.

All FEH methods are based on relationships between flood frequency behaviour and catchment properties, quantified as catchment descriptors. These were previously calculated for all sites on a digitised version of the UK river network at 50-metre resolution.

Care should also be given to the numerical precision applied to any results obtained using these methods. The degree of precision displayed in these worked examples may be higher than what could be reliably attained from these methods/data. This is to demonstrate the mathematical steps and theory rather than how they should be applied in practice.

4.1 Example – rural catchment

Estimates the 1-in-12-month, 1-in-2-year, 1-in-30-year and 1-in-100-year flood peaks and runoff volumes for Severn at Plynlimon flume (NRFA no. 54022). The catchment descriptors for Severn at Plynlimon Flume are shown in Table 6.

Table 6 – Catchment descriptors for Severn at Plynlimon Flume

Catchment descriptor	Value
AREA	8.75 km^2
SAAR	2481 mm
FARL	1.000
BFIHOST	0.323
$URBEXT_{2000}$	0
FPEXT	0.0098
DPLBAR	2.94 km
DPSBAR	180.3 m/km
PROPWET	0.66

4.1.1 Flood peak estimates from gauged data (at-site analysis):

The Plynlimon station is considered suitable for pooling-group analysis in the NRFA Peak Flow dataset (The associated NRFA website is available at: https://nrfa.ceh.ac.uk/data/station/info/54022). This indicates some confidence in the measured annual maxima. In version 7 of the NRFA Peak Flow dataset (current at the time of analysis), the record length is 38 years, suggesting that at-site data can safely be used to estimate floods with return periods up to 19 years but will be unreliable above that. The 1-in-2 year flood is simply estimated as the median value of the 38 annual maxima.

At this station, QMED = 14.99 m^3/s.

The 1-in-12-months flood can be derived entirely from at-site data by fitting a distribution to the 38 annual maxima and reading the flow corresponding to a 1.58-year return period. By inspection, several distributions (generalised logistic, generalised extreme value, Pearson type III and three-parameter lognormal) fit the observed data almost equally, when only the 19 AMAX smaller than QMED are considered. Therefore, the generalised logistic (GLO) distribution is used for convenience. Standardising all 38 AMAX by QMED gives the L-moment ratios and GLO parameter values of:

- L-CV = 0.156
- L-SKEW = 0.171
- $\beta = 0.156$
- $\kappa = -0.171$
- (ξ = QMED = 14.99)

Using the GLO distribution (Equation 17) by Kjeldsen and others (2008) the 1-in-12-months flood can be calculated as shown in Equation 6:

Equation 6 – Calculating the 1-in-12-months flood

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

$$x_{1.58} = 14.99\left[1 - \frac{0.156}{0.171}\left(1 - 0.58^{0.171}\right)\right]$$

The 1-in-12-month flood peak = 13.77 m^3/s.

Disclaimer on the use of at-site analyses:

It is important to note that the gauged estimates of the 1-in-12 months and 1-in-2-year flood peaks are still only estimates of the true values, albeit usually the most accurate ones. Several factors influence the distance between the gauged estimate and the true value of the flood peaks, including, but not limited to, the length of gauging period, measurement uncertainty, sensitivity of the measurement structure/device and presence/absence of climatic trends. Uncertainty relating to the length of the gauging period is known as ‘sampling uncertainty’ and is quantified below:

Uncertainty in flood peak estimates from gauged data:

The record length of 38 years for Severn at Plynlimon Flume is considerably longer than either the one-year or two-year return period of the flood in question, but still subject to some uncertainty, because the 38 available AMAX are a sample from the full flood frequency distribution. Equation 2.6 of ‘Making better use of local data in flood frequency estimation’ (Environment Agency, 2017) suggests that the factorial standard error (fse) in QMED, for a 38-year AMAX record with $\beta = 0.156$ and $\kappa = -0.171$, is approximately 1.05.

Therefore, the 95% confidence interval in the gauged estimate of QMED is:

- [QMED / 1.052, QMED × 1.052] or
- 13.59 m^3/s < QMED < 16.53 m^3/s (~91-110% of gauged estimate)

Environment Agency (2017) does not give information on how to calculate fse in estimates of shorter return period floods, so it is precautionary to assume that the same range applies to both QMED and the 1-in-12-month flood:

- 12.49 m^3/s < 1-in-12-month flood peak < 15.18 m^3/s (~91-110% of gauged estimate)

4.1.2 Flood peak estimates from combined gauged and regional data (enhanced single-site analysis):

While the 38-year AMAX record for Severn at Plynlimon Flume is too short to estimate the 1-in-30-year and 1-in-100-year floods, this lack of data can be overcome by combining the Plynlimon AMAX record with other AMAX records gauged in similar catchments.

Catchment similarity is measured using the similarity distance measure (SDM), which was revised as part of this project. The original measure is shown in Equation 7:

Equation 7 – The original SDM

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

Equation 8 shows the new SDM :

Equation 8 – The new SDM

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

WINFAP 4 (used in this study)applies the original SDM for all catchment sizes. The derivation of the new measure is set out in Section 8.4 with the result in Equation 27, Although FARL and FPEXT were not selected, these should be considered in some cases if they are important at the stations concerned. For example, FARL should be considered for small catchments with important reservoirs.

Using the original measure gives the following pooling-group shown in Table 7 (using WINFAP 4 with version 7 of the NRFA Peak Flow dataset files). The recommended pooling-group size is to use the minimum number of station records required to give at least 500 AMAX. The weighting scheme presented by Kjeldsen and others (2008) is unchanged, that is, at-site data receive an enhanced weight in the calculation of L-CV but not L-SKEW.

Table 7 – Pooling-group (using WINFAP 4 with version 7 of the NRFA Peak Flow dataset files)

Station	SDM	Years	L-CV	L-SKEW
54022 (Severn @ Plynlimon Flume)	0.000	38	0.156	0.171
92002 (Allt Coire Nan Con @ Polloch)	0.144	16	0.101	0.337
91802 (Allt Leachdach @ Intake)	0.420	34	0.153	0.257
71003 (Croasdale Beck @ Croasdale Flume)	0.603	37	0.212	0.323
25003 (Trout Beck @ Moor House)	0.716	44	0.168	0.294
57017 (Rhondda Fawr @ Tynewydd)	0.899	16	0.123	-0.076
206006 (Annalong @ Recorder)	1.021	48	0.189	0.052
25011 (Langdon Beck @ Langdon)	1.141	28	0.238	0.318
28033 (Dove @ Hollinsclough)	1.177	38	0.234	0.405
49006 (Camel @ Camelford)	1.181	11	0.124	-0.185
47022 (Tory Brook @ Newnham Park)	1.305	24	0.265	0.138
46005 (East Dart @ Bellever)	1.392	53	0.157	0.057
45816 (Haddeo @ Upton)	1.416	24	0.306	0.387
49003 (de Lank @ de Lank)	1.615	51	0.225	0.206
48009 (st Neot @ Craigshill Wood)	1.659	12	0.245	0.373
27032 (Hebden Beck @ Hebden)	1.678	51	0.204	0.247

Station	SDM	Years	L-CV	L-SKEW
Weighted means	N/A	N/A	**0.167**	**0.210**

The weighted mean L-moments give GLO distribution parameters of:

- $\beta = 0.164$ and $\kappa = -0.210$

(Note: ξ is still estimated from gauged data at Plynlimon; QMED = 14.99)

Using the GLO distribution in the form given by Kjeldsen and others (2008), with $T = 1.58$, $T = 30$ and $T = 100$ gives:

- 1-in-12-month flood peak = 13.72 m^3/s
- 1-in-30-year flood peak = 27.03 m^3/s
- 1-in-100-year flood peak = 34.01 m^3/s

Using the new measure gives the following pooling-group and data shown in Table 8 (L-CV etc) (using version 7 of the NRFA Peak Flow dataset files). The station selection was by the user’s own approach in WINFAP 4. WINFAP 5 now applies this new SDM for small catchments. The recommendations on pooling-group size and enhanced weighting of at-site data are unchanged.

Table 8 – Pooling-group (using version 7 of the NRFA Peak Flow dataset files)

Station	SDM	Years	L-CV	L-SKEW
54022 (Severn @ Plynlimon Flume)	0.000	38	0.156	0.171
92002 (Allt Coire Nan Con @ Polloch)	0.094	16	0.101	0.337
91802 (Allt Leachdach @ Intake)	0.245	34	0.153	0.257
57017 (Rhondda Fawr @ Tynewydd)	0.509	16	0.123	-0.076
25003 (Trout Beck @ Moor House)	0.785	44	0.168	0.294
71003 (Croasdale Beck @ Croasdale Flume)	0.808	37	0.212	0.323
46005 (East Dart @ Bellever)	0.884	53	0.157	0.057
76001 (Haweswater Beck @ Burnbanks)	1.035	38	0.424	0.124
206006 (Annalong @ Recorder)	1.147	48	0.189	0.052
73009 (Sprint @ Sprint Mill)	1.244	48	0.180	0.199
49003 (de Lank @ de Lank)	1.403	51	0.225	0.206
46007 (West Dart @ Dunnabridge)	1.482	36	0.177	0.162
25012 (Harwood Beck @ Harwood)	1.534	48	0.191	0.234
Weighted means	N/A	N/A	**0.165**	**0.184**

The weighted mean L-moments give GLO distribution parameters of:

- $\beta = 0.164$ and $\kappa = -0.184$

(Note: ξ is still estimated from gauged data at Plynlimon; QMED = 14.99)

Using the GLO distribution in the form given by Kjeldsen and others (2008), with $T = 1.58$, $T = 30$ and $T = 100$ gives:

- 1-in-12-month flood peak = 13.72 m^3/s

- 1-in-30-year flood peak = 26.46 m^3/s
- 1-in-100-year flood peak = 32.76 m^3/s

The pooling-group generated using the new SDM has nine members (including Plynlimon) in common with the pooling-group generated by the original SDM.

The derived default pooling-group should be reviewed - though changes have not been included in these calculations to give revised values.

The group should be inspected for catchments with outlying L-moments, which may be removed if they result from considerable hydrological differences with the catchment of interest. Note that it is **never** acceptable to remove a site with outlying L-moments, if those L-moments result purely from outlying real storm events. The group should also be reviewed based on knowledge and information about particular stations.

76001 (Haweswater Beck @ Burnbanks) has been included in the station selection above. This has an L-CV of 0.423 and FARL of 0.645. Haweswater reservoir drains nearly all the catchment to Burnbanks. As the site of interest (54022, Severn @ Plynlimon Flume) is not at all influenced by reservoirs or lakes, Burnbanks (76001) should be removed from the pooling-group. Similarly, Low Nibthwaite (FARL 0.73) would be removed from the pooling-group. Removed stations should be replaced with suitable unused stations with the lowest SDM scores.

‘Making better use of local data in flood frequency estimation’ (Environment Agency, 2017) does not give information on how to calculate fse in estimates of longer return period floods, other than stating that it is related to variance in QMED, variance in the growth factor, and covariance between the two, and that the last two terms need to consider the effects of dependence between different AMAX series in the pooling-group. Mosteller (1946) gave a now well-established expression for the asymptotic variance of any quantile of any continuous probability distribution (Equation 9), which can be used to estimate the theoretical uncertainty in any T-year flood, where p = 1 – 1/T. However, this is likely to greatly overestimate the actual uncertainty, due to the previously mentioned covariance, both between uncertainties in QMED and the growth curve, and between individual AMAX series contributing to the growth curve.

Equation 9 – Mosteller’s expression for asymptotic variance of any quantile of any continuous probability distribution

$$\sigma^2 = \frac{p(1-p)}{nf^2\left(F^{-1}(p)\right)}$$

4.1.3 QMED linking equation

If gauged data are not enough to estimate AMAX, but enough to estimate base flow index and daily mean flows up to those exceeded on 5% of days, then the QMED linking equation can be used. This is generally preferable to estimating QMED through purely ungauged estimation but not as good as estimating QMED from AMAX data. The QMED linking equation is shown in Equation 10:

Equation 10 – The QMED linking equation

$$QMED = 1.762 Q5_{DMF}^{0.866} (1 + GRADQ5_{DMF})^{-0.775} DPSBAR^{0.265} 0.2388^{BFI^2}$$

Here, $Q5_{DMF}$ is the daily mean flow exceeded on 5% of days, $GRADQ5_{DMF}$ is the gradient from $Q5_{DMF}$ to $Q10_{DMF}$ (daily mean flow exceeded on 10% of days) using a log-normal approximation and BFI is the gauged base flow index – not BFIHOST. These data are given or can be derived from the NRFA – for this station: https://nrfa.ceh.ac.uk/data/station/info/54022. $Q5_{DMF}$ and $GRADQ5_{DMF}$ can be obtained or derived from the Daily flow data page, and DPSBAR from the Peak flow data > Data type > FEH catchment descriptors.

Retrieving these flow statistics from the NRFA website gives:

- QMED = 18.44 m^3/s (~123% of gauged estimate)

The fse of this equation is 1.31, so the 95% confidence interval is:

- 10.75 m^3/s < QMED < 31.64 m^3/s (~72-211% of gauged estimate)

The QMED estimate from the QMED linking equation must be integrated with a growth curve to estimate flood peaks for return periods other than QMED. The fact that the QMED linking equation is used to estimate QMED, rather than AMAX data, suggests that an enhanced single-site analysis is not possible. Therefore, the FEH statistical method (see below) is used to estimate the growth factors associated with other return period floods.

4.1.4 FEH statistical method

This project recommends to continue applying the current FEH statistical method whenever a statistical, FEH-compatible estimate of QMED is required.

The existing FEH statistical equation for QMED gives a statistical estimate of the 1-in-2-year flood (shown in Equation 11):

Equation 11 – FEH statistical estimate of the 1-in-2- year flood

$$QMED = 8.3062 AREA^{0.8510} 0.1536^{\frac{1000}{SAAR}} FARL^{3.4451} 0.0460^{BFIHOST^2}$$

$$QMED = 17.93\ m^3/s\ (\sim 120\%\ \text{of gauged estimate})$$

This equation only gives the statistical ‘best guess’ for QMED; the modelling framework is subject to structural uncertainty, which is reported in terms of factorial standard error (fse). Kjeldsen and others (2008) report the fse of this equation as 1.431. Therefore, this can be used to report the estimate of QMED as a range.

The 95% confidence interval for QMED is given by:

- [QMED / 1.431^2, QMED × 1.431^2] or
- 8.76 m^3/s < QMED < 36.72 m^3/s (~58-245% of gauged estimate)

Note that the 95% confidence interval for QMED from the FEH statistical equation is far larger than the 95% confidence interval for QMED from the gauged AMAX record.

Donor transfer is a process where the ratio of the gauged QMED estimate to statistical QMED estimate is used to improve a purely statistical estimate at a site of interest. The best donor site is one with the same tendency to over or underestimation as the site of interest, as the donor will ‘cancel out’ this tendency. Over and underestimation tendencies in the FEH statistical QMED equation are spatially correlated. Therefore, this project recommends selecting one donor based on geographical distance only.

Hore at Hore Flume (NRFA no. 54092) is 0.83 km from Severn at Plynlimon Flume with a catchment area 37% of that to Plynlimon flume.

Using this station as a donor gives:

- QMED = 15.38 m^3/s (~103% of gauged estimate)

The reduced fse for this estimate of QMED with one donor is 1.231 (reported in WINFAP 4), so the 95% confidence interval is given by:

- 10.15 m^3/s < QMED < 23.31 m^3/s (~68-155% of gauged estimate)

Donor transfer has narrowed the 95% confidence interval somewhat, although it remains considerably wider than that for a gauged QMED estimate.

In the FEH statistical method, the full flood-frequency relationship for floods other than QMED is estimated by multiplying QMED with a dimensionless growth curve, which relates the fraction x_T/QMED to T, where x_T is the T-year flood. This growth relationship is normally taken as a generalised logistic (GLO) distribution in the UK and is parameterised at ungauged sites by pooling weighted average L-moments from hydrologically similar sites to the site of interest, using a similarity distance measure (SDM) to measure similarity. The current SDM and the new recommended SDM for small catchments are both given previously in this worked example.

Using the original measure gives the following pooling-group shown in Table 9 (using WINFAP 4 with version 7 of the NRFA). It is noted that this is almost the same as that generated for enhanced single-site analysis, with the site of interest being removed and one more site added to bring the total number of years back above 500. No L-moments are given enhanced weight in an ungauged analysis.

Table 9 – Pooling-group (using WINFAP 4 with version 7 of the NRFA)

Station	SDM	Years	L-CV	L-SKEW
92002 (Allt Coire Nan Con @ Polloch)	0.144	16	0.101	0.337
91802 (Allt Leachdach @ Intake)	0.420	34	0.153	0.257
71003 (Croasdale Beck @ Croasdale Flume)	0.603	37	0.212	0.323
25003 (Trout Beck @ Moor House)	0.716	44	0.168	0.294
57017 (Rhondda Fawr @ Tynewydd)	0.899	16	0.123	-0.076
206006 (Annalong @ Recorder)	1.021	48	0.189	0.052
25011 (Langdon Beck @ Langdon)	1.141	28	0.238	0.318
28033 (Dove @ Hollinsclough)	1.177	38	0.234	0.405
49006 (Camel @ Camelford)	1.181	11	0.124	-0.185
47022 (Tory Brook @ Newnham Park)	1.305	24	0.265	0.138
46005 (East Dart @ Bellever)	1.392	53	0.157	0.057
45816 (Haddeo @ Upton)	1.416	24	0.306	0.387
49003 (de Lank @ de Lank)	1.615	51	0.225	0.206
48009 (st Neot @ Craigshill Wood)	1.659	12	0.245	0.373
27032 (Hebden Beck @ Hebden)	1.678	51	0.204	0.247
25012 (Harwood Beck @ Harwood)	1.688	48	0.191	0.234
Weighted means	N/A	N/A	**0.191**	**0.221**

The weighted mean L-moments give GLO distribution parameters of:

- $\beta = 0.192$ and $\kappa = -0.221$

(Note: ξ is still estimated from the QMED equation with one donor; 15.38)

Using the GLO distribution in the form given by Kjeldsen and others (2008) with T = 1.58, T = 30 and T = 100 gives:

- 1-in-12-month flood peak = 13.86 m^3/s (101% of gauged estimate)
- 1-in-30-year flood peak = 30.14 m^3/s (114% of enhanced single-site estimate)
- 1-in-100-year flood peak = 38.91 m^3/s (119% of enhanced single-site estimate)

Equation 2.12 in Environment Agency (2017) allows crude estimation of the fse associated with an FEH statistical flood estimate rarer than QMED. Using this gives:

- $fse_{T=1.58}$ = 1.429
- $fse_{T=30}$ = 1.486
- $fse_{T=100}$ = 1.528

This leads to 95% confidence intervals of:

- 6.79 m^3/s < 1-in-12-month flood peak < 28.31 m^3/s (~49-206% of enhanced single-site estimate)
- 13.65 m^3/s < 1-in-30-year flood peak < 66.56 m^3/s (~52-252% of enhanced single-site estimate)
- 16.66 m^3/s < 1-in-100-year flood peak < 90.84 m^3/s (~51-277% of enhanced single-site estimate)

Using the new measure gives the following pooling-group shown in Table 10 (using WINFAP 4 with version 7 of the NRFA Peak Flow dataset).

Table 10 – Pooling-group (using WINFAP 4 with version 7 of the NRFA Peak Flow dataset)

Station	SDM	Years	L-CV	L-SKEW
92002 (Allt Coire Nan Con @ Polloch)	0.094	16	0.101	0.337
91802 (Allt Leachdach @ Intake)	0.245	34	0.153	0.257
57017 (Rhondda Fawr @ Tynewydd)	0.509	16	0.123	-0.076
25003 (Trout Beck @ Moor House)	0.785	44	0.168	0.294
71003 (Croasdale Beck @ Croasdale Flume)	0.808	37	0.212	0.323
46005 (East Dart @ Bellever)	0.884	53	0.157	0.057
76001 (Haweswater Beck @ Burnbanks)	1.035	38	0.424	0.124
206006 (Annalong @ Recorder)	1.147	48	0.189	0.052
73009 (Sprint @ Sprint Mill)	1.244	48	0.180	0.199
49003 (de Lank @ de Lank)	1.403	51	0.225	0.206
46007 (West Dart @ Dunnabridge)	1.482	36	0.177	0.162
25012 (Harwood Beck @ Harwood)	1.534	48	0.191	0.234
25011 (Langdon Beck @ Langdon)	1.543	28	0.238	0.318
21017 (Ettrick Water @ Brockhoperig)	1.553	41	0.203	0.276
Weighted means	N/A	N/A	**0.190**	**0.203**

The weighted mean L-moments give GLO distribution parameters of:

- $\beta = 0.189$ and $\kappa = -0.203$

(Note: ξ is still estimated from the QMED equation with one donor; 15.38)

Using the GLO distribution in the form given by Kjeldsen and others (2008) with T = 1.58, T = 30 and T = 100 gives:

- 1-in-12-month flood peak = 13.88 m^3/s (101% of enhanced single-site estimate)
- 1-in-30-year flood peak = 29.43 m^3/s (111% of enhanced single-site estimate)
- 1-in-100-year flood peak = 37.46 m^3/s (114% of enhanced single-site estimate)

Equation 2.12 in Environment Agency (2017) allows crude estimation of the fse associated with an FEH statistical flood estimate rarer than QMED. Using this gives:

- $fse_{T=1.58} = 1.429$
- $fse_{T=30} = 1.486$
- $fse_{T=100} = 1.528$

Leading to 95% confidence intervals of:

- 6.80 m^3/s < 1-in-12-month flood peak < 28.35 m^3/s (~50-207% of enhanced single-site estimate)
- 13.33 m^3/s < 1-in-30-year flood peak < 64.98 m^3/s (~50-246% of enhanced single-site estimate)
- 16.04 m^3/s < 1-in-100-year flood peak < 87.45 m^3/s (~49-267% of enhanced single-site estimate)

4.1.5 ReFH2 method

Catchment descriptors for Severn at Plynlimon Flume, provided at the beginning of the example, are repeated here for convenience (see Table 11).

Table 11 – Catchment descriptors for Severn at Plynlimon Flume

Catchment descriptor	Value
AREA	8.75 km^2
SAAR	2481 mm
FARL	1.000
BFIHOST	0.323
URBEXT$_{2000}$	0
FPEXT	0.0098
DPLBAR	2.94 km
DPSBAR	180.3 m/km
PROPWET	0.66

ReFH2 contains no provision for storage routing, so is considered not suitable for catchments with FARL < 0.9. In this example, FARL is 1, so this aspect is not relevant.

Loading the catchment descriptor XML file gives the following model parameters and initial conditions, derived from catchment descriptor equations for catchments in England, Wales or Northern Ireland (shown in Table 12).

Table 12 - Model parameters and initial conditions, derived from catchment descriptor equations for catchments in England, Wales or Northern Ireland

Parameter	Value
C_{max}	224.262 mm
T_p	1.098 hours
BL	23.952 hours
BR	0.962
C_{ini}	129.766 mm
BF_0	1.252 m^3/s

As $URBEXT_{2000}$ = 0, winter initial conditions are calculated, and the urbanisation parameters are not relevant to this example. T_p is slightly over one hour. If it were calculated as less than one hour, it should be rounded up to exactly one hour.

The design storm duration is calculated as:

- $D = T_p(1 + SAAR/1000)$
- D = 3.822 hours

All design storms for use in ReFH2 are single-peaked and symmetrical, so they must be composed of an odd number of time steps. The calculated design storm duration of 3.822 hours is therefore rounded to 3.75 hours, composed of 15 quarter-hour modelling time steps.

The ReFH2 software interpolates FEH2013 rainfall depths from tables in the XML file, then automatically applies the areal reduction factor (ARF) and seasonal correction factor (SCF) for a winter storm, giving the following rainfall depths shown in Table 13:

Table 13 – Rainfall depths

Return period	Depth
1-in-12 months	29.09 mm
1-in-2 years	32.85 mm
1-in-30 years	66.70 mm
1-in-100 years	83.78 mm

The areal reduction factor and seasonal correction factor are calculated, using equations published in Kjeldsen and others (2007), as 0.949 and 0.922 respectively. As $URBEXT_{2000}$ = 0, a winter storm profile is produced. It should be noted here that ReFH2 refers to a ‘one year’ event. This is equal to the 1-in-12-month event (POT scale) or 1-in-1.58-year event (AMAX scale).

ReFH2’s event modelling screen gives the following results for peak flow shown in Table 14:

Table 14 – Peak flows

Return period	Peak flow
1-in-12 months	18.90 m^3/s (138% of at-site estimate)
1-in-2 years	21.47 m^3/s (143% of at-site estimate)
1-in-30 years	47.25 m^3/s (179% of enhanced single-site estimate)
1-in-100 years	62.11 m^3/s (190% of enhanced single-site estimate)

Environment Agency (2017) estimates a factorial standard error for ReFH2 at QMED (fse = 1.48), but not at any other return periods:

- 9.80 m^3/s < 1-in-2-year peak flow < 47.03 m^3/s (~65-314% of enhanced single-site estimate)

For runoff volumes, ReFH2's event modelling screen gives the following results shown in Table 15:

Table 15 – Runoff volumes

Return period	Runoff volume
1-in-12 months	321.59 Ml
1-in-2 years	367.56 Ml
1-in-30 years	832.44 Ml
1-in-100 years	1101.13 Ml

Your study may require a 100 year 6-hour event. In order to estimate the 6-hour, 100-year peak flow and runoff volume, it is necessary to divide six hours into an odd number of time steps – a discretisation into 25 time steps of 14 minutes 24 seconds each is selected, as this time step is very close to the default quarter-hour modelling time step for this catchment. This increases the net rainfall depth, after applying an increased ARF (0.957) and SCF (0.948), to 104.39 mm. The peak flow and runoff for this event are:

- 6-hour, 1-in-100-year peak flow: 65.15 m^3/s
- 6-hour, 1-in-100-year runoff volume: 1436.35 Ml

Tables 16, 17 and 18 show the comparison of flood peak estimates made by different methods. The results have been presented as derived.

Table 16 - Flood peak estimates - strongly recommended methods

Method	1-in-12 month	1-in-2 year	1-in-30 year	1-in-100 year
At-site	13.77	14.99	N/A	N/A
Enhanced single-site (new SDM)	13.88	14.99	26.46	32.76

Table 17 - Flood peak estimates - recommended methods

Method	1-in-12 month	1-in-2 year	1-in-30 year	1-in-100 year
FEH statistical (1 donor, new SDM)	13.88	15.38	29.43	37.46
FEH statistical (QMED linking equation, new SDM)	16.64	18.44	35.28	44.91
ReFH2	18.90	21.47	47.25	62.11

Table 18 - Flood peak estimates – other methods

Method	1-in-12 month	1-in-2 year	1-in-30 year	1-in-100 year
Enhanced single-site (existing SDM)	13.72	14.99	27.03	34.01
FEH statistical (0 donors, existing SDM)	16.16	17.93	35.14	45.36
FEH statistical (0 donors, new SDM)	16.18	17.93	34.30	43.67
FEH statistical (1 donor, existing SDM)	13.86	15.38	30.14	38.91

In some projects, some further consideration might be required. For example, if the QMED of 14.99m3/s is accepted, then the ReFH2 growth factor would estimate the 100-year peak as 43.4m3/s.

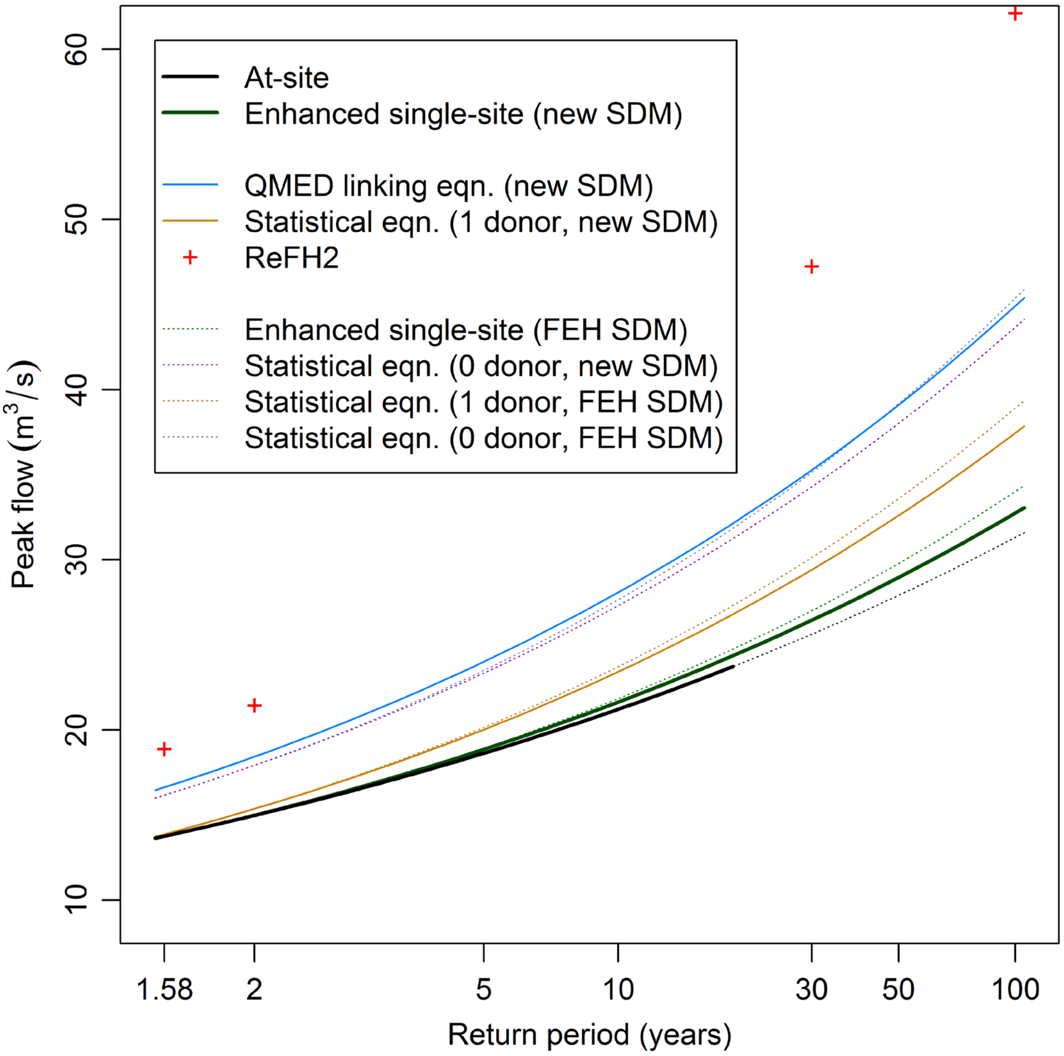

Figure 12 - Comparison of flood peak estimates made by different methods

The line graph in Figure 12 shows flood peak estimates made by different methods plotted by return period (1.58-100 years – x-axis) and peak flow (10-60 m^3/s – y-axis). It should be noted that a return period of 1.58 years on the annual maximum scale used in the figure is equivalent to a 12- month return period using a peak-over-threshold scale. The legend divides the methods by the extent to which they are recommended as follows:

- strongly recommended:
  - at-site – bold black line
  - enhanced single-site (new SDM) – bold green line
- recommended methods:
  - QMED linking eqn. (new SMD) - blue line
  - statistical eqn. (1 donor, new SDM) - yellow line
  - ReFH2 (red cross)
- other methods:
  - enhanced single-site (FEH SDM) - dotted green line

- statistical eqn. (0 donor, new SDM) - dotted purple line
- statistical eqn. (1 donor, FEH SDM) - dotted yellow line
- statistical eqn. (0 donor, FEH SDM) - dotted green line

4.2 Example – urban catchment

Estimates the 1-in-12-month, 1-in-2-year, 1-in-30-year and 1-in-100-year flood peaks and runoff volumes for Oulton Beck at Oulton Farrer Lane (NRFA no. 27081). Catchment descriptors for Oulton Beck at Oulton Farrer Lane are shown in Table 19.

Table 19 - Catchment descriptors for Oulton Beck at Oulton Farrer Lane

Catchment Descriptor	Value
AREA	25.10 km^2
SAAR	677 mm
FARL	0.997
BFIHOST	0.535
$URBEXT_{2000}$	0.2235
FPEXT	0.0486
DPLBAR	6.86 km
DPSBAR	40.4 m/km
PROPWET	0.32

Although the area of this catchment is very slightly above the 25 km^2 limit for using small catchment methods, it is used in this worked example as it is a small urban catchment in the dataset that is also rated as “suitable for pooling”.

4.2.1 Flood peak estimates from gauged data (at-site analysis):

The station flow data are considered suitable for pooling-group analysis by the Environment Agency. The record length is 31 years, suggesting that at-site data can safely be used to estimate floods with return periods up to 15.5 years.

The 1-in-2-year flood is simply estimated as the median value of the 31 annual maxima:

- QMED = 2.40 m^3/s

The 1-in-12 months flood can be derived entirely from at-site data by fitting a distribution to the 31 annual maxima and reading the flow corresponding to a 1.58-year return period. By inspection, several distributions (generalised logistic, generalised extreme value, Pearson type III and three-parameter lognormal) fit the observed data almost equally, when only the 15 AMAX smaller than QMED are considered. Therefore, the generalised logistic (GLO) distribution is used for convenience. Standardising all 31 AMAX by QMED gives the following L-moment ratios and GLO parameter values of:

- L-CV = 0.246
- L-SKEW = 0.260
- $\beta = 0.245$
- $\kappa = -0.260$
- (ξ = QMED = 2.40)

Equation 12 shows the calculation of the 1-in-12 months flood using the GLO distribution in the form given by Kjeldsen and others (2008):

Equation 12 – Using the GLO distribution for flood estimation

$$x_{1.58} = 2.40\left[1 - \frac{0.245}{0.260}\left(1 - 0.58^{0.260}\right)\right]$$

- the 1-in-12-month flood peak = 2.10 m^3/s

Equation 2.6 of Environment Agency (2017) suggests that the factorial standard error (fse) in QMED, for a 31-year AMAX record with $\beta = 0.245$ and $\kappa = -0.260$, is approximately 1.1. Therefore, the 95% confidence interval in the gauged estimate of QMED is:

- 1.98 m^3/s < QMED < 2.90 m^3/s (~83-121% of gauged estimate)

Assuming that the same fse applies to both QMED and the 1-in-12-month flood:

- 1.74 m^3/s < 1-in-12-month flood peak < 2.54 m^3/s (~83-121% of gauged estimate)

4.2.2 Flood peak estimates from combined gauged and regional data (enhanced single-site analysis):

Using the original SDM gives the following pooling-group (using WINFAP 4 with version 7 of the NRFA Peak Flow dataset). The weighting scheme presented by Kjeldsen and others (2008) is unchanged, that is, at-site data receive an enhanced weight in the calculation of L-CV but not L-SKEW.

Because the site of interest is heavily urbanised, at-site L-moments must be deurbanised before they can be pooled with L-moments from the 13 rural catchments comprising the rest of the pooling-group. The following default relationships are used to urbanise and deurbanise L-moments:

- $\text{L-CV}_{urban} = \text{L-CV}_{rural} \times 0.5547^{URBEXT_{2000}}$
- $0.246 = \text{L-CV}_{rural} \times 0.5547^{0.2235}$
- $\text{L-CV}_{rural} = 0.281$
- $\text{L-SKEW}_{urban} = \left[(\text{L-SKEW}_{rural} + 1) \times 1.1545^{\text{URBEXT}_{2000}}\right] - 1$
- $0.260 = \left[(\text{L-SKEW}_{rural} + 1) \times 1.1545^{0.2235}\right] - 1$
- $\text{L-SKEW}_{rural} = 0.220$

Using the new measure gives the following pooling-group and data shown in Table 20 (L-CV etc) (using version 7 of the NRFA Peak Flow dataset). . The station selection was by the user’s own approach in WINFAP 4. WINFAP 5 now applies this new SDM for small catchments. The recommendations on pooling-group size and enhanced weighting of at-site data are unchanged.

Table 20 – Pooling-group and data (using version 7 of the NRFA Peak Flow dataset)

Station	SDM	Years	L-CV	L-SKEW
27081 (Oulton Beck @ Oulton Farrer Lane)	0.000	31	0.281	0.220
36010 (Bumpstead Brook @ Broad Green)	0.303	50	0.371	0.177
26803 (Water Forlornes @ Driffield)	0.527	18	0.312	0.133
7011 (Black Burn @ Pluscarden Abbey)	0.634	5	0.582	0.464
26802 (Gypsey Race @ Kirby Grindalythe)	0.707	18	0.316	0.217
41020 (Bevern Stream @ Clappers Bridge)	0.769	48	0.203	0.175
28058 (Henmore Brook @ Ashbourne)	0.837	12	0.155	-0.064
39033 (Winterbourne Stream @ Bagnor)	0.852	55	0.345	0.388
25019 (Leven @ Easby)	0.874	39	0.340	0.377
203046 (Rathmore Burn @ Rathmore Bridge)	0.881	35	0.147	0.144
20002 (West Peffer Burn @ Luffness)	0.894	41	0.292	0.015
44008 (South Winterbourne @ Winterbourne Steepleton)	0.908	38	0.417	0.336
27010 (Hodge Beck @ Bransdale Weir)	0.935	41	0.224	0.293
44013 (Piddle @ Little Puddle)	0.939	25	0.500	0.273
24007 (Browney @ Lanchester)	0.943	15	0.222	0.212
53017 (Boyd @ Bitton)	0.955	44	0.244	0.094

Station	SDM	Years	L-CV	L-SKEW
Weighted means	N/A	N/A	**0.290**	**0.213**

The weighted mean L-moments above must be re-urbanised before fitting the distribution. Applying the same equations as before gives the following L-CV and L-SKEW, and subsequently the following GLO distribution parameters:

- L-CV = 0.254
- L-SKEW = 0.252
- $\beta = 0.254$
- $\kappa = -0.252$

(Note: ξ is still estimated from gauged data; QMED = 2.40)

Using the GLO distribution in the form given by Kjeldsen and others (2008), with T = 1.58, T = 30 and T = 100 gives:

- 1-in-12-month flood peak = 2.09 m^3/s
- 1-in-30-year flood peak = 5.63 m^3/s
- 1-in-100-year flood peak = 7.68 m^3/s

Using the new measure gives the following pooling-group shown in Table 21 (using WINFAP 4 with version 7 of the NRFA Peak Flow Dataset). The recommendations on pooling-group size and enhanced weighting of at-site data are unchanged.

Table 21 - Pooling-group (using WINFAP 4 with version 7 of the NRFA Peak Flow Dataset)

Station	SDM	Years	L-CV	L-SKEW
27081 (Oulton Beck @ Oulton Farrer Lane)	0.000	31	0.281	0.220
20002 (West Peffer Burn @ Luffness)	0.271	41	0.292	0.015
26803 (Water Forlornes @ Driffield)	0.271	18	0.312	0.133
36010 (Bumpstead Brook @ Broad Green)	0.411	50	0.371	0.177
26802 (Gypsey Race @ Kirby Grindalythe)	0.484	18	0.316	0.217
39033 (Winterbourne Stream @ Bagnor)	0.495	55	0.345	0.388
33054 (Babingey @ Castle Rising)	0.523	41	0.204	0.080
7011 (Black Burn @ Pluscarden Abbey)	0.586	5	0.582	0.464
26013 (Driffield Trout Stream @ Driffield)	0.599	6	0.317	0.340
33032 (Heacham @ Heacham)	0.639	49	0.307	0.120
24007 (Browney @ Lanchester)	0.653	15	0.222	0.212
36004 (Chad Brook @ Long Melford)	0.680	50	0.297	0.178
26003 (Foston Beck @ Foston Mill)	0.690	57	0.250	0.010
30004 (Lymn @ Partney Mill)	0.692	55	0.231	0.055
20006 (Biel Water @ Belton House)	0.707	28	0.375	0.128
Weighted means	N/A	N/A	**0.290**	**0.164**

The re-urbanised weighted mean L-moments and GLO distribution parameters are:

- L-CV = 0.254
- L-SKEW = 0.201
- $\beta = 0.259$
- $\kappa = -0.201$

(Note: ξ is still estimated from gauged data; QMED = 2.40.)

Using the GLO distribution in the form given by Kjeldsen and others (2008), with T = 1.58, T = 30 and T = 100 gives:

- 1-in-12-month flood peak = 2.08 m^3/s
- 1-in-30-year flood peak = 5.39 m^3/s
- 1-in-100-year flood peak = 7.10 m^3/s

The derived default pooling-group should be reviewed - though changes have not been included in these calculations to give revised values.

The group should be inspected for catchments with outlying L-moments, which may be removed if they result from considerable hydrological differences with the catchment of interest. It is not acceptable to remove a site with outlying L-moments if those L-moments result purely from outlying real storm events. The group should also be reviewed based on knowledge and information about particular stations.

Here, the L-moments for 7011 (Black Burn @ Pluscarden Abbey) are based on just five years of data, so the very high L-CV and L-SKEW values may reasonably be assumed to originate from sampling uncertainty. Also, Driffield (26013) has six years' of data and comparatively high L-CV and L-SKEW values. Many users would judge to remove these stations.

Environment Agency (2017) does not give information on how to calculate fse in estimates of longer return period floods.

4.2.3 QMED linking equation

The QMED linking equation was developed using and calibrated entirely to flow data from catchments with $URBEXT_{2000} < 0.06$. Its performance and potential limitations in more urbanised catchments are therefore unknown, so the equation cannot be recommended for this catchment.

4.2.4 FEH statistical method

The recommendation from this project is to continue applying the current FEH statistical method whenever a statistical, FEH-compatible estimate of QMED is required.

The existing FEH statistical equation for QMED gives a statistical estimate of the 1-in-2-year flood (Equation 13):

Equation 13 – FEH statistical equation for QMED

$$QMED = 8.3062 AREA^{0.8510} 0.1536^{\frac{1000}{SAAR}} FARL^{3.4451} 0.0460^{BFIHOST^2}$$

$$QMED = 3.32\ \mathrm{m^3/s} \quad (\sim 138\%\ \text{of gauged estimate})$$

The 95% confidence interval for QMED is given by:

- [QMED / 1.431^2, QMED × 1.431^2]
- 1.62 m^3/s < QMED < 6.80 m^3/s (~68-283% of gauged estimate)

Note that the 95% confidence interval for QMED from the FEH statistical equation is far larger than the 95% confidence interval for QMED from the gauged AMAX record.

Selecting one donor based on geographical distance only gives Crimple at Burn Bridge (NRFA no. 27051), which is 26.05 km away.

This gives a donor adjusted QMED of:

- QMED = 3.41 m^3/s (~142% of gauged estimate)

It is noted that this donor is a considerable distance away from the site of interest. The reduced fse for this estimate of QMED with one donor is 1.412 (reported in WINFAP 4), so the 95% confidence interval is given by:

- 1.71 m^3/s < QMED < 6.80 m^3/s (~71-283% of gauged estimate)

In this case, donor transfer has only narrowed the 95% confidence interval very slightly.

Using the original measure gives the following pooling-group shown in Table 22 (using WINFAP 4 with version 7 of the NRFA Peak Flows Dataset). It is noted that this is almost the same as that generated for enhanced single-site analysis with the site of interest being removed and one more site added to bring the total number of years back above 500. No L-moments are given enhanced weight in an ungauged analysis.

Table 22 – Pooling-group (using WINFAP 4 with version 7 of the NRFA Peak Flows Dataset)

Station	SDM	Years	L-CV	L-SKEW
36010 (Bumpstead Brook @ Broad Green)	0.303	50	0.371	0.177
26803 (Water Forlornes @ Driffield)	0.527	18	0.312	0.133
7011 (Black Burn @ Pluscarden Abbey)	0.634	5	0.582	0.464
26802 (Gypsey Race @ Kirby Grindalythe)	0.707	18	0.316	0.217
41020 (Bevern Stream @ Clappers Bridge)	0.769	48	0.203	0.175
28058 (Henmore Brook @ Ashbourne)	0.837	12	0.155	-0.064
39033 (Winterbourne Stream @ Bagnor)	0.852	55	0.345	0.388
25019 (Leven @ Easby)	0.874	39	0.340	0.377
203046 (Rathmore Burn @ Rathmore Bridge)	0.881	35	0.147	0.144
20002 (West Peffer Burn @ Luffness)	0.894	41	0.292	0.015
44008 (South Winterbourne @ Winterbourne Steepleton)	0.908	38	0.417	0.336
27010 (Hodge Beck @ Bransdale Weir)	0.935	41	0.224	0.293
44013 (Piddle @ Little Puddle)	0.939	25	0.500	0.273
24007 (Browney @ Lanchester)	0.943	15	0.222	0.212
53017 (Boyd @ Bitton)	0.955	44	0.244	0.094

Station	SDM	Years	L-CV	L-SKEW
36004 (Chad Brook @ Long Melford)	1.025	50	0.297	0.178
Weighted means	N/A	N/A	**0.306**	**0.208**

The reurbanised weighted mean L-moments give GLO distribution parameters of

- L-CV = 0.268
- L-SKEW = 0.248
- $\beta = 0.271$
- $\kappa = -0.248$

(Note: ξ is still estimated from the QMED equation with one donor; 3.41.)

Using the GLO distribution in the form given by Kjeldsen and others (2008) with T = 1.58, T = 30 and T = 100 gives:

- 1-in-12-month flood peak = 2.94 m^3/s (140% of at-site estimate)
- 1-in-30-year flood peak = 8.27 m^3/s (153% of enhanced single-site estimate)
- 1-in-100-year flood peak = 11.33 m^3/s (160% of enhanced single-site estimate)

Equation 2.12 in Environment Agency (2017) allows crude estimation of the fse associated with an FEH statistical flood estimate rarer than QMED. Using this gives:

- $fse_{T=1.58} = 1.429$
- $fse_{T=30} = 1.486$
- $fse_{T=100} = 1.528$

Leading to 95% confidence intervals of:

- 1.44 m^3/s < 1-in-12-month flood peak < 6.00 m^3/s (~69-288% of at-site estimate)
- m^3/s < 1-in-30-year flood peak < 18.27 m^3/s (~70-339% of enhanced single-site estimate)
- 4.85 m^3/s < 1-in-100-year flood peak < 26.45 m^3/s (~68-373% of enhanced single-site estimate)

Using the new measure gives the following pooling-group shown in Table 23 (using WINFAP 4 with version 7 of the NRFA Peak Flows Dataset).

Table 23 – Pooling-group (using WINFAP 4 with version 7 of the NRFA Peak Flows Dataset)

Station	SDM	Years	L-CV	L-SKEW
20002 (West Peffer Burn @ Luffness)	0.271	41	0.292	0.015
26803 (Water Forlornes @ Driffield)	0.271	18	0.312	0.133
36010 (Bumpstead Brook @ Broad Green)	0.411	50	0.371	0.177
26802 (Gypsey Race @ Kirby Grindalythe)	0.484	18	0.316	0.217
39033 (Winterbourne Stream @ Bagnor)	0.495	55	0.345	0.388
33054 (Babingey @ Castle Rising)	0.523	41	0.204	0.080
7011 (Black Burn @ Pluscarden Abbey)	0.586	5	0.582	0.464
26013 (Driffield Trout Stream @ Driffield)	0.599	6	0.317	0.340
33032 (Heacham @ Heacham)	0.639	49	0.307	0.120
24007 (Browney @ Lanchester)	0.653	15	0.222	0.212
36004 (Chad Brook @ Long Melford)	0.680	50	0.297	0.178
26003 (Foston Beck @ Foston Mill)	0.690	57	0.250	0.010
30004 (Lymn @ Partney Mill)	0.692	55	0.231	0.055
20006 (Biel Water @ Belton House)	0.707	28	0.375	0.128
25019 (Leven @ Easby)	0.709	39	0.340	0.377
Weighted means	N/A	N/A	**0.309**	**0.166**

The re-urbanised weighted mean L-moments give GLO distribution parameters of:

- L-CV = 0.271
- L-SKEW = 0.205
- $\beta = 0.277$
- $\kappa = -0.205$

(Note: ξ is still estimated from the QMED equation with one donor; 3.41.)

Using the GLO distribution in the form given by Kjeldsen and others (2008) with T = 1.58, T = 30 and T = 100 gives:

- 1-in-12-month flood peak = 2.92 m^3/s (139% of at-site estimate)
- 1-in-30-year flood peak = 7.99 m^3/s (154% of enhanced single-site estimate)
- 1-in-100-year flood peak = 10.62 m^3/s (154% of enhanced single-site estimate)

The GLO distribution gives 95% confidence intervals of:

- 1.43 m^3/s < 1-in-12-month flood peak < 5.97 m^3/s (~69-287% of enhanced single-site estimate)
- 3.62 m^3/s < 1-in-30-year flood peak < 17.65 m^3/s (~67-327% of enhanced single-site estimate)
- 4.55 m^3/s < 1-in-100-year flood peak < 24.80 m^3/s (~64-349% of enhanced single-site estimate)

4.2.5 ReFH2 method

Catchment descriptors for Oulton Beck at Farrer Lane, provided at the beginning of the example, are repeated in Table 24 for convenience:

Table 24 - Catchment descriptors for Oulton Beck at Farrer Lane

Catchment Descriptor	Value
AREA	25.10 km^2
SAAR	677 mm
FARL	0.997
BFIHOST	0.535
$URBEXT_{2000}$	0.2235
FPEXT	0.0486
DPLBAR	6.86 km
DPSBAR	40.4 m/km
PROPWET	0.32

As FARL here is almost 1, using ReFH2 cannot be immediately ruled out on storage routing grounds.

Loading the catchment descriptor XML file gives the following model parameters and initial conditions (shown in Table 25), derived from catchment descriptor equations for catchments in England, Wales or Northern Ireland:

Table 25 - Model parameters and initial conditions, derived from catchment descriptor equations for catchments in England, Wales or Northern Ireland

Parameter	Value
C_{max}	453.098 mm
T_p	6.529 hours
BL	54.371 hours
BR	1.301
C_{ini}	105.615 mm
BF_0	0.698 m^3/s

As $URBEXT_{2000} \geq 0.15$, but BFIHOST < 0.65, winter initial conditions are calculated and as-rural, rather than urbanised, modelling results are relevant.

The design storm duration is calculated as:

- $D = T_p(1 + SAAR/1000)$
- D = 10.949 hours

All design storms for use in ReFH2 are single-peaked and symmetrical, so they must be composed of an odd number of time steps. The calculated design storm duration of 10.949 hours is therefore rounded to 11 hours, composed of 11 hourly modelling time steps.

The ReFH2 software interpolates FEH2013 rainfall depths from tables in the XML file, then automatically applies the areal reduction factor (ARF = 0.952) and seasonal correction factor (SCF = 0.698) from Kjeldsen and others (2007) for a winter storm, giving the following rainfall depths shown in Table 26:

Table 26 – Rainfall depths

Return period	Depth
1-in-12 months	17.13 mm
1-in-2 years	18.97 mm
1-in-30 years	36.77 mm
1-in-100 years	46.87 mm

Note here that what ReFH2 refers to as a ‘one year’ event is the 1-in-12-month event (POT scale) or 1-in-1.58-year event (AMAX scale).

ReFH2’s event modelling screen gives the following results for as-rural peak flow (shown in Table 27):

Table 27 – As-rural peak flows

Return period	Peak flow
1-in-12 months	3.24 m^3/s (156% of at-site estimate)
1-in-2 years	3.55 m^3/s (148% of at-site estimate)
1-in-30 years	6.81 m^3/s (126% of enhanced single-site estimate)
1-in-100 years	8.85 m^3/s (125% of enhanced single-site estimate)

Environment Agency (2017) estimates a factorial standard error for ReFH2 at QMED (fse = 1.48), but not at any other return periods: 1.62 m^3/s < 1-in-2-year peak flow < 7.78 m^3/s (~68-324% of enhanced single-site estimate).

For runoff volumes, ReFH2’s event modelling screen gives the following as-rural results (shown in Table 28):

Table 28 – As-rural runoff volumes

Return period	Runoff volume
1-in-12 months	250.08 Ml
1-in-2 years	280.28 Ml
1-in-30 years	581.92 Ml
1-in-100 years	771.56 Ml

In order to estimate the 6-hour, 100-year peak flow and runoff volume, it is necessary to divide six hours into an odd number of time steps – a discretisation into nine time steps of 40 minutes each is selected, as this is reasonably close to the default time step of one hour. This reduces the net rainfall depth, after applying ARF (0.939) and SCF (0.693), to 40.68 mm. The as-rural peak flow and runoff volume for this event are:

- 6-hour, 1-in-100-year peak flow: 8.24 m^3/s
- 6-hour, 1-in-100-year runoff volume: 653.28 Ml

For precautionary estimates of peak flow, urbanised results are used (Table 29). However, the Tp scaling factor is increased from 0.5 to 1, as $URBEXT_{2000} < 0.3$. Note that estimated total runoff volume is reduced, as urbanised baseflow is calculated to be smaller than as rural-baseflow.

Table 29 – Urbanised peak flows and runoff volumes when Tp scaling factor is set to 1

Parameter	Value
1-in-12-month peak flow	3.59 m^3/s (173% of at-site estimate)
1-in-2-year peak flow (QMED)	3.94 m^3/s (164% of at-site estimate)
1-in-30-year peak flow	7.50 m^3/s (139% of enhanced single-site estimate)
1-in-100-year peak flow	9.70 m^3/s (137% of enhanced single-site estimate)
1-in-12-month runoff volume	221.60 Ml
1-in-2-year runoff volume	247.22 Ml
1-in-30-year runoff volume	507.75 Ml
1-in-100-year runoff volume	670.40 Ml
6-hour, 1-in-100-year peak flow	9.13 m^3/s
6-hour, 1-in-100-year runoff volume	568.77 Ml

For completeness, the urbanised results with a Tp scaling factor of 0.5, as recommended previously, are presented in Table 30:

Table 30 - Urbanised peak flows and runoff volumes when Tp scaling factor is set to 0.5

Parameter	Value
1-in-12-month peak flow	3.91 m^3/s (188% of at-site estimate)
1-in-2-year peak flow (QMED)	4.29 m^3/s (179% of at-site estimate)
1-in-30-year peak flow	8.15 m^3/s (151% of enhanced single-site estimate)
1-in-100-year peak flow	10.51 m^3/s (148% of enhanced single-site estimate)
1-in-12-month runoff volume	221.60 Ml
1-in-2-year runoff volume	247.22 Ml
1-in-30-year runoff volume	507.75 Ml
1-in-100-year runoff volume	670.40 Ml
6-hour, 1-in-100-year peak flow	10.12 m^3/s
6-hour, 1-in-100-year runoff volume	568.77 Ml

Tables 31, 32 and 33 show the comparison of flood peak estimates made by different methods. The results are presented as derived.

Table 31 - Flood peak estimates – strongly recommended methods

Method	1-in-12 month	1-in-2 year	1-in-30 year	1-in-100 year
At-site	2.10	2.40	N/A	N/A
Enhanced single-site (new SDM)	2.08	2.40	5.39	7.10

Table 32 - Flood peak estimates – recommended methods

Method	1-in-12 month	1-in-2 year	1-in-30 year	1-in-100 year
FEH statistical (1 donor, new SDM)	2.92	3.41	7.99	10.62
ReFH2 (as-rural)	3.24	3.55	6.81	8.85

Table 33 - Flood peak estimates – other methods

Method	1-in-12 month	1-in-2 year	1-in-30 year	1-in-100 year
Enhanced single-site (existing SDM)	2.09	2.40	5.63	7.68
FEH statistical (0 donors, existing SDM)	2.86	3.32	8.05	11.03
FEH statistical (0 donors, new SDM)	2.85	3.32	7.78	10.34
FEH statistical (1 donor, existing SDM)	2.94	3.41	8.27	11.33
ReFH2 (urban, unenhanced routing)	3.59	3.94	7.50	9.70
ReFH2 (urban, enhanced routing)	3.91	4.29	8.15	10.51

In some projects, some further consideration might be required. For example, if the QMED of 2.40m^3/s is accepted, then the ReFH2 (as rural) growth factor would estimate the 100-year peak as 6.0m^3/s – ReFH2 has lower growth factors than the FEH Statistical methods.

For this example, ReFH2 as-rural is recommended over either variant of ReFH2 urban because the URBEXT$_{2000}$ value of 0.2235 is lower than the threshold of 0.3, below which the effects of urbanisation on runoff are not usually apparent, except in catchments that are both dry (SAAR < 800 mm) **and** permeable (BFIHOST ≥ 0.65). However, if a conservatively high estimate of peak flow is required for a specific project, then one of the urban estimates can be used, with the choice informed by the level of conservatism required.

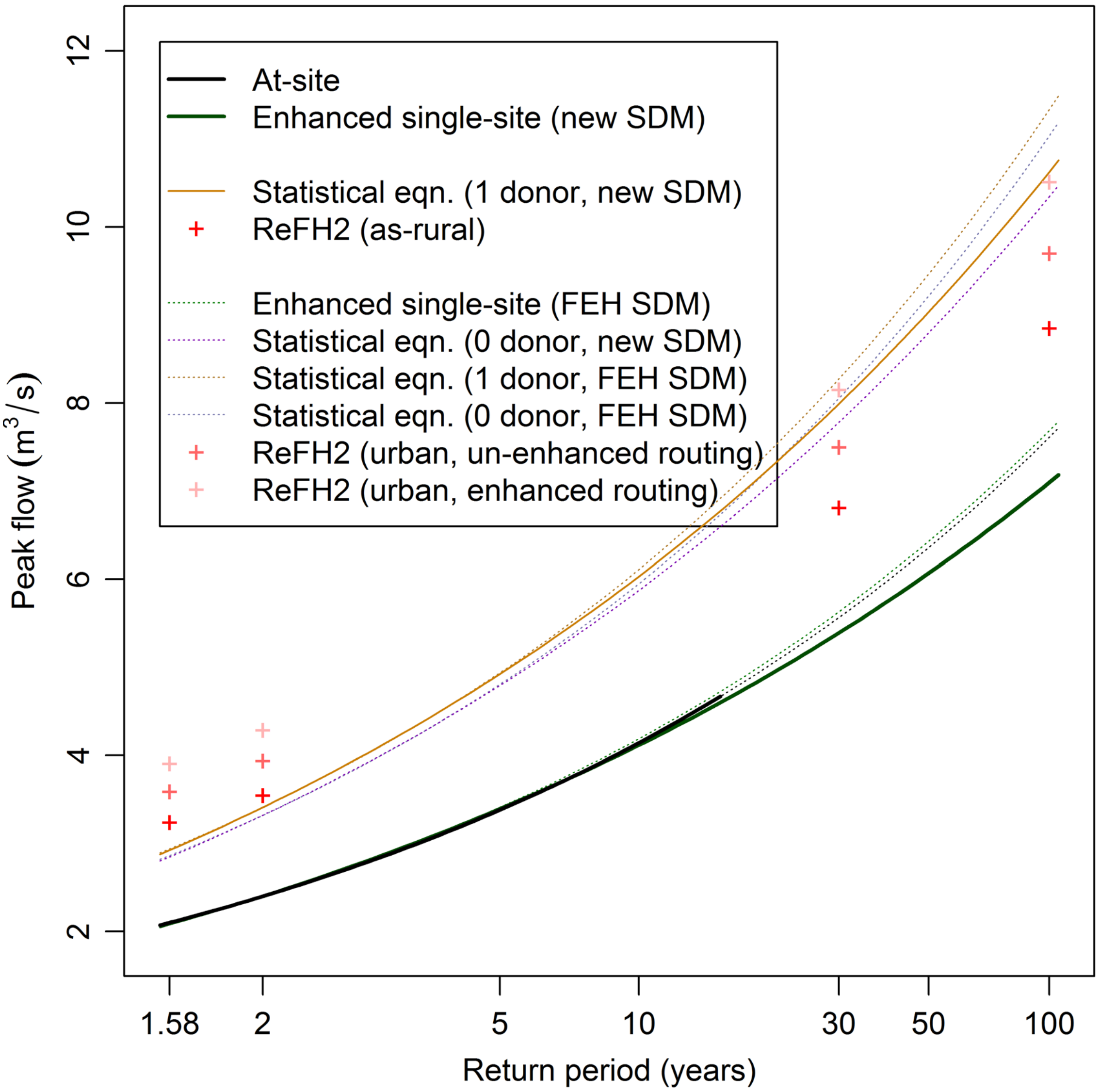

Figure 13 - Comparison of flood peak estimates made by different methods

Figure 13 shows flood peak estimates made by different methods plotted by return period (1.58-100 years – x-axis) and peak flow (2-12 m^3/s – y-axis). It should be noted that a return period of 1.58 years on the annual maximum scale used in the figure is equivalent to a 12- month return period using a peak-over-threshold scale. The legend divides the methods by the extent to which they are recommended as follows:

- strongly recommended:
  - at-site – bold black line
  - enhanced single-site (new SDM) – bold green line
- recommended methods:
  - statistical eqn. (1 donor, new SDM) - yellow line
  - ReFH2 (as-rural) - red cross

- other methods:
    - enhanced single-site (FEH SDM) - dotted green line
    - statistical eqn. (0 donor, new SDM) - dotted purple line
    - statistical eqn. (1 donor, FEH SDM) - dotted yellow line
    - statistical eqn. (0 donor, FEH SDM) - dotted green line
    - ReFH2 (urban, un-enhanced routing) - orange cross
    - ReFH2 (urban, enhanced routing) - pink cross

4.3 Example – plot-scale analysis

Estimate the 1-in-12-month, 1-in-2-year, 1-in-30-year and 1-in-100-year greenfield flood peaks and runoff volumes for a 50-ha plot at SU6200090000. Relevant descriptors are shown in Table 34:

Table 34 – Catchment descriptors

Catchment descriptor	Value
AREA	0.50 km^2
SAAR	600 mm
BFIHOST	0.889
PROPWET	0.29

Note that results, but not worked examples, are presented for the FEH statistical method (with one donor and new SDM) and ReFH2 (with catchment-scale equations), as the previously described worked example (“rural catchment”) already shows, worked examples to apply these methods in rural catchments. Also, note that all peak flow results are presented in units of l/s/ha. For a catchment area of 50 ha, they can be converted to m^3/s by dividing by 20.

4.3.1 FEH statistical method

Pang at Pangbourne (39027) is used as a donor, because of the plot centroid of this station being close to the site. Assuming FARL = 1. QMED is estimated below:

- use QMED FEH Statistical catchment descriptors equation for both the plot-scale site and for Pangbourne

- compare the Pangbourne estimate with the gauged QMED, and apply FEH donor method to adjust for the plot-scale location QMED estimate:
- QMED = 0.219 l/s/ha
- 0.111 l/s/ha < QMED < 0.430 l/s/ha

Using the new SDM with version 7 of the NRFA Peak Flows Dataset gives the following GLO distribution parameters:

- $\kappa = -0.214$
- $\beta = 0.277$.
- (Note: $\xi = 0.219$ l/s/ha)

These generate the following flood peak estimates:

- 1-in-12-month flood peak = 0.188 l/s/ha.
- 1-in-30-year flood peak = 0.513 l/s/ha.
- 1-in-100-year flood peak = 0.682 l/s/ha

The estimates have the following 95% confidence intervals:

- 0.092 l/s/ha < 1-in-12-month flood peak < 0.384 l/s/ha.
- 0.235 l/s/ha < 1-in-30-year flood peak < 1.144 l/s/ha.
- 0.297 l/s/ha < 1-in-100-year flood peak < 1.619 l/s/ha

4.3.2 ReFH2

As the plot has no drainage network, standard catchment-descriptor equations cannot be used to estimate model parameters. Instead, plot-scale equations, which use AREA in place of DPLBAR and SAAR in place of DPSBAR, are used, to estimate the following parameter values and initial conditions shown in Table 35:

Table 35 – Parameter values and initial conditions

Parameter	Value
C_{max}	1160.273 mm
T_p	2.453 hours
BL	60.442 hours
BR	2.253
C_{ini}	59.256 mm
BF_0	0 m^3/s

The design storm duration is 3.925 hours, which is discretised into seven steps of 30 minutes (3.5 hours). The following peak flow, 95% confidence interval, and runoff volumes are given (shown in Table 36).

Table 36 - Peak flow, 95% confidence interval, and runoff volumes

Parameter	Value
1-in-12-month peak flow	0.410 l/s/ha
1-in-2-year peak flow (QMED)	0.484 l/s/ha
1-in-30-year peak flow	1.216 l/s/ha
1-in-100-year peak flow	1.608 l/s/ha
95% confidence interval	0.221 l/s/ha < 1-in-2-year peak flow (QMED) < 1.060 l/s/ha
1-in-12-month runoff volume	0.315 Ml
1-in-2-year runoff volume	0.372 Ml
1-in-30-year runoff volume	0.934 Ml
1-in-100-year runoff volume	1.240 Ml

The 6-hour, 100-year results are:

- 6-hour, 100-year peak flow = 1.778 l/s/ha
- 6-hour, 100-year runoff volume = 1.540 Ml

4.3.3 Free screening tool for estimating greenfield runoff rates and volumes

The new screening tool does not use standard FEH catchment descriptors. Instead, it uses free equivalents: $SAAR_{4170}$ and BFI_{SGDBE}, which are the average annual rainfall over the period 1941 to 1970 and the estimate of baseflow index from the European Soil Data Centre's Soils Geographical Database of Eurasia. Refer to Section 13.2 of this report for further details.

The equation for volume (Equation 14) also uses x, easting on the British national grid where 1 = 1,000 km.

Equation 14 - The equation for volume

$$\ln Q_T = -2.65 + 0.206 \ln T - 1.67 BFI_{SGDBE} + 1.38 \left(\frac{SAAR_{4170}}{1{,}000} \right)$$

Separate equations are used for the 6-hour, 100-year peak flow (Equation 15) and runoff volume (Equation 16).

Equation 15 - 6-hour, 100-year peak flow volume

$$\ln Q_{100,6\mathrm{h}} = -0.96 + 1.07 \left(\frac{SAAR_{4170}}{1{,}000} \right) - 1.81 BFI_{SGDBE}$$

Equation 16 - 6-hour, 100-year runoff volume

$$\ln \mathrm{Vol}_{100,6\mathrm{h}} = 8.64 + x \left(0.2 \frac{SAAR_{4170}}{1{,}000} - 0.4 BFI_{SGDBE} \right)$$

In these equations, Q_T is in units of m^3/s while Vol_T is in units of m^3 (Ml/1,000).

It is noted that the equations do not contain any area terms; they are intended to calculate peak flow for a 50-hectare area. Estimates for smaller areas should be obtained by scaling the 50-hectare estimates linearly by area. For this plot of land, BFI_{SGDBE} = 0.959, $SAAR_{4170}$ = 599 mm and x = 0.462. The results in Table 37 are presented 'per-hectare'.

Table 37 – Results

Parameter	Value
$Q_{1.58}$	0.715 l/s/ha
Q_2	0.751 l/s/ha
Q_{30}	1.312 l/s/ha
Q_{100}	1.681 l/s/ha
$Q_{100,6h}$	2.562 l/s/ha
$Vol_{100,6h}$	5.004 Ml

Factorial standard errors (fse) are tabulated for return periods of two and 100 years. They are: 2.11 (2-year peak), 2.05 (100-year peak), 2.01 (100-year, 6-hour peak) and 1.95, (100-year, 6-hour volume). Therefore, the 95% confidence intervals for the above estimates are:

- 0.169 l/s/ha < Q_2 < 3.344 l/s/ha
- 0.400 l/s/ha < Q_{100} < 7.064 l/s/ha
- 0.634 l/s/ha < $Q_{100,6h}$ < 10.351 l/s/ha
- 1.316 Ml < $Vol_{100,6h}$ < 19.028 Ml

Note the widths of these confidence intervals – in all cases, the top of the interval is more than 14 times larger than the bottom of the interval, while for the 100-year peak flow, the bottom of the interval is below the central estimate for the 1-in-12-month peak. This reflects the relative precision and quality of the free descriptors used in the free methods, as well as the requirement for the estimates to be conservative on average.

5. Peak flow data available to the study

5.1 Sources of peak flow data

This section summarises the set of peak flow data for 217 small catchments made available to the study. Some parts of the UK such as Scotland and the West Midlands are not well represented in the data set mainly due to issues with data quality. Urban catchments are not particularly well represented in the data set, but average permeability and annual rainfall characteristics are similar to average values across the whole NRFA peak flow data set.

Further details are provided in **project report R1**.

This section gives a summary of the data used in the project, particularly in exploring QMED estimation methods and developing new pooling procedures for small catchments.

During the early part of the project, a set of 'high-quality' peak flow data for small catchments was developed. Although the main emphasis was on catchments with an area less than 25 km^2, suitable catchments with areas up to 40.9 km^2 were included. This was to allow for a transition zone between small and intermediate-sized catchments, to permit integration between existing generic methods and those developed specifically for small catchments.

Details of the initial selection of 154 gauged catchments for this project are given in project report R1 (Data collection report). Three gauges were removed from the data set since they were not classified as suitable for estimating QMED, but two more gauges were added from the NRFA peak flow data, together with 64 gauges that had been used in the study of small catchments by MacDonald and Fraser (2013). After the baseline assessment described in Section 6 was completed, but before the work on new methods described in Sections 7 and 8 began, one catchment was removed from the data set.

The full data set consists of 217 small catchments (216 after the baseline assessment), split according to their suitability for estimating QMED and rarer flood peaks (QT) into 'high-quality' and 'extended' subsets. This is based on QMED/pooling suitability criteria and the availability of AMAX series. The number of gauged catchments in each subset is given in Table 38 (bracketed values indicate totals after the baseline assessment). Table 39 provides a summary of the 'extended' QMED data set compared with the catchments of less than 40.9 km^2 used in previous major studies. The number of station-years of data used in this study is almost three times that used in the analysis leading to the development of the existing FEH statistical method.

Table 38 - Summary of data sets used in QMED and QT analysis

Data set	Number of stations
'High-quality' QMED	153 (152)
'Extended' QMED	217 (216)
'High-quality' QT	59 (58)
'Extended' QT	192 (191)

Table 39 - Summary of 'extended' QMED data set and comparison with previous studies (< 40.9 km2)

Measure	This study (2017)	Existing FEH (2008)	FEH (1999)
No. of gauges	217	85	117
Shortest record length	4	4	3
Longest record length	64	56	56
Mean record length	27.4	25.6	17.7
No. AMAX events	5946	2180	2071

5.2 Overview of data characteristics

Figure 14 is a location map of the 217 catchments in the 'extended' QMED data set, indicating whether each catchment has flow peak data or simply a QMED value available. It is clear that some parts of the UK such as Scotland and the West Midlands are not well represented in the data set and this is mainly due to issues with data quality, especially in urban catchments.

FEH catchment descriptors can be used to illustrate the range of catchment types within the data set and three descriptors are discussed here. BFIHOST (baseflow index derived from the HOST soil classification) is an index of catchment responsiveness which provides a broad indication of average permeability. Values of BFIHOST exceeding 0.65 are generally taken to indicate permeable catchments. SAAR (mm) is a standard-period mean annual rainfall averaged across the catchment and URBEXT_{2000} is an index of the extent of the catchment area that is urbanised.

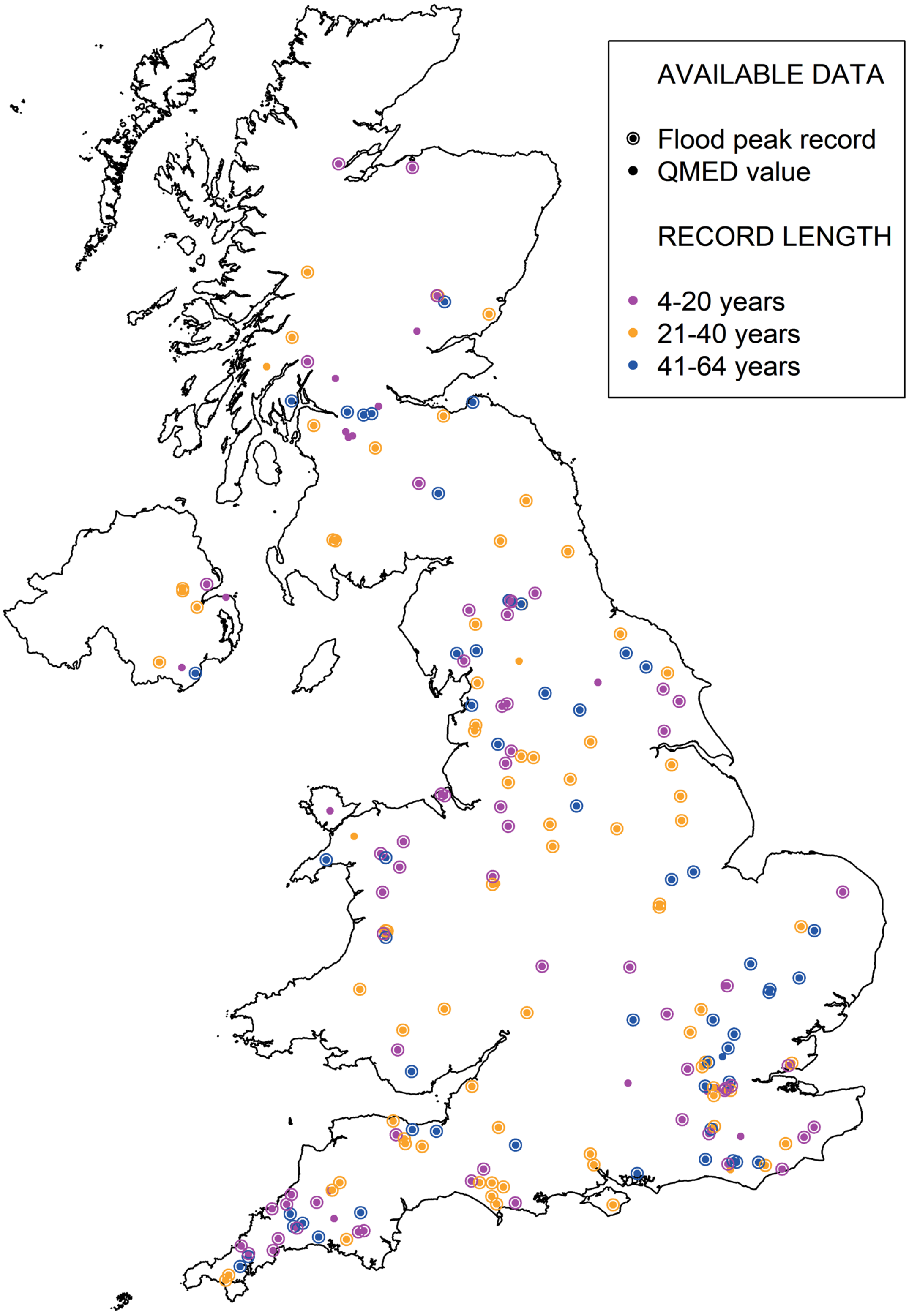

Figure 14 - Location map of small catchments in the full project ('extended QMED') data set

The map in Figure 14 plots the 217 catchments in the 'extended' QMED data set, indicating whether flow peak data (marked with dots within circles) or simply a QMED value (marked with small dots) is available for each catchment. Varying record lengths are marked using three colours:

- 4-20 years (purple dots)
- 21-40 years (yellow dots)
- 41-64 years (blue dots)

Figure 15 presents the spatial distribution of BFIHOST and SAAR, highlighting the most permeable catchments in red on the left-hand plot and the catchments with highest average annual rainfall in blue on the right-hand plot. The catchments falling into broad categories of urbanisation are mapped in Figure 16. Relatively few of the catchments are in the heavily urbanised category (defined by an $URBEXT_{2000}$ value of greater than or equal to 0.15) and most of these are in south-east England.

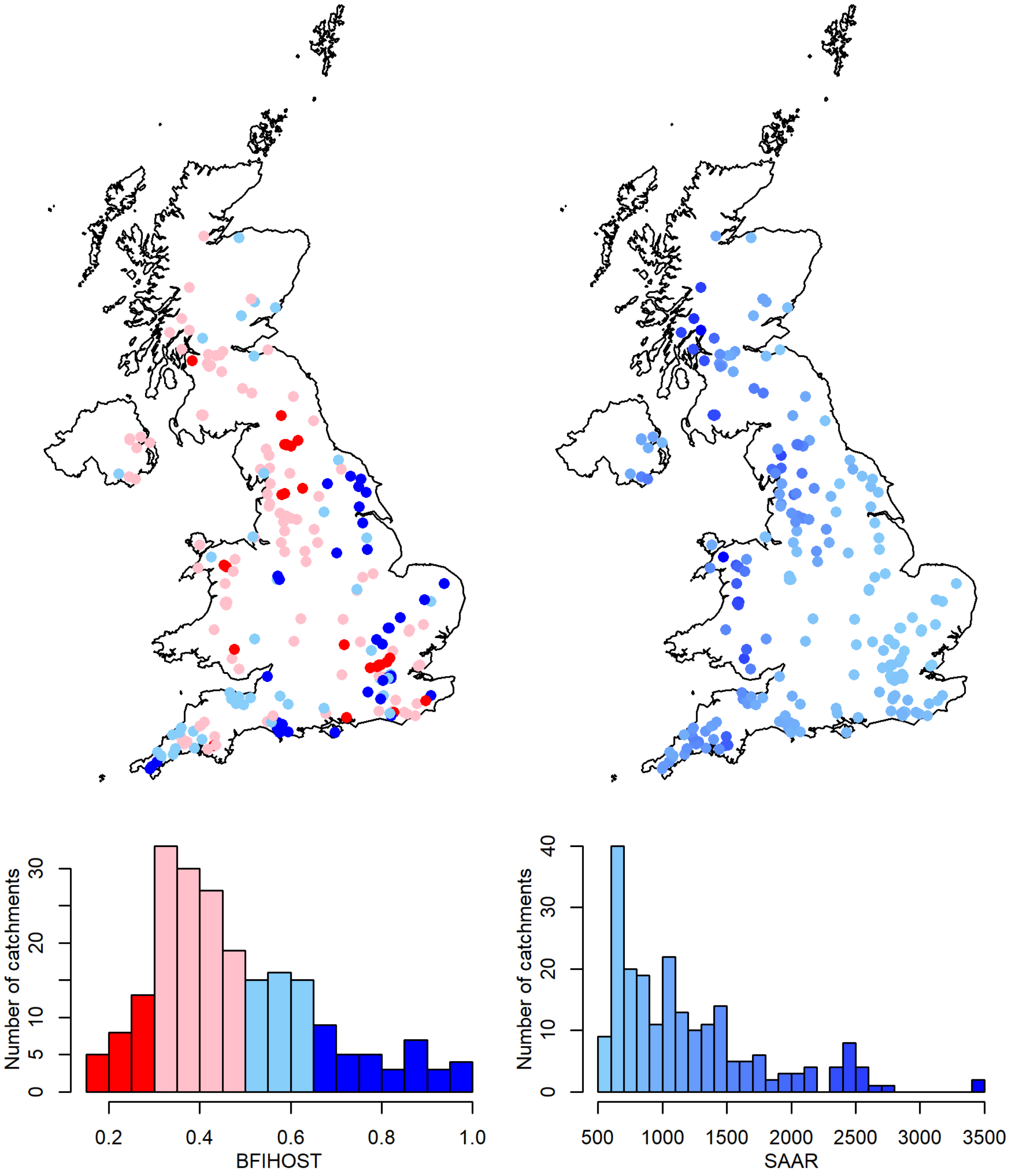

Figure 15 - Maps and histograms showing the distribution of BFIHOST and SAAR within the full project data set

The maps and bar charts in Figure 15 present the spatial distribution of BFIHOST (left-hand side) and SAAR (right-hand side). The left-hand figure and graph show the permeability of the catchments ranging from dark blue (least permeable) to light blue, pale red and bold red (most permeable). The right-hand figure and graph show the levels of rainfall ranging from light blue (least rainfall) to dark blue (highest rainfall).

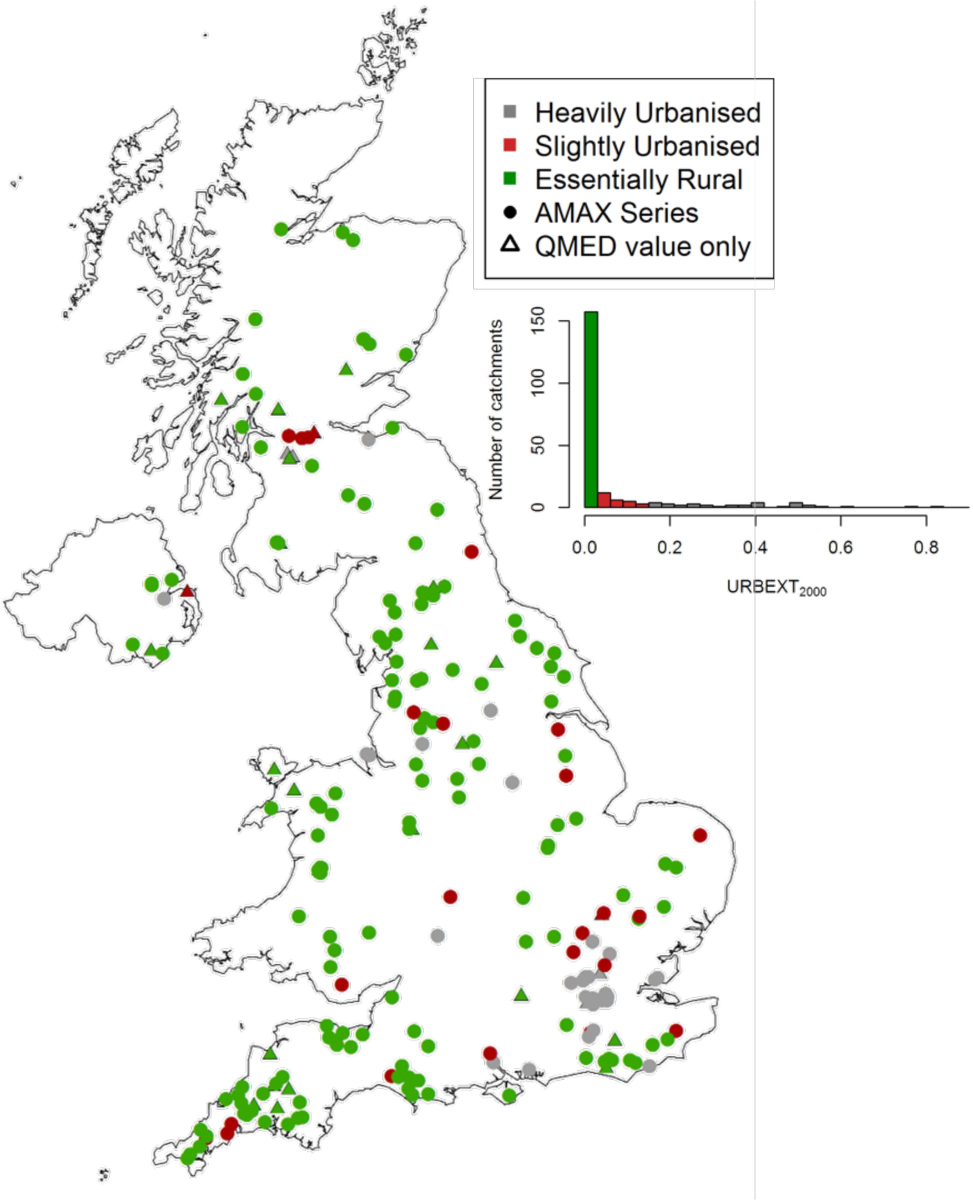

Figure 16 - Locations of small, urbanised catchments with AMAX series

The map and graph in Figure 16 show the catchments falling into broad categories of urbanisation:

- heavily urbanised (grey symbols)
- slightly urbanised (red symbols)
- essentially rural (green symbols)
- AMAX series (coloured dots)

- QMED value only (coloured triangles)

Table 40 summarises the number of catchments in the project data set together with the range and median values of the BFIHOST, SAAR and $URBEXT_{2000}$ catchment descriptors in comparison to the NRFA Peak Flow data overall. The median values of BFIHOST and SAAR within the two data sets are very similar, while the range of all three descriptor values is slightly larger in the data set of the current study. However, the study data set is somewhat less urbanised than the NRFA peak flow data set, which itself is not highly urbanised in general.

Table 40 - Catchment descriptor summaries for the study data set and NRFA peak flow data v3.3.4

Statistic	NFRA peak flow	Study dataset
Count	962	217
Minimum BFIHOST	0.172	0.172
Median BFIHOST	0.468	0.437
Maximum BFIHOST	0.974	0.985
Minimum SAAR (mm)	555	552
Median SAAR (mm)	971	1043
Maximum SAAR (mm)	2913	3473
Minimum $URBEXT_{2000}$	0.0000	0.0000
Median $URBEXT_{2000}$	0.0089	0.0050
Maximum $URBEXT_{2000}$	0.5917	0.8110

6. Baseline assessment of methods

A summary of comparisons of the performance of existing flood estimation methods is presented in this section, based on separate analyses for rural and urban catchments. Performance at return periods of two and 100 years is emphasised, although selected return periods up to 1,000 years are also considered. Since the analysis was carried out before ReFH2.2 was developed, the ReFH2 method was applied together with FEH99 design storm inputs.

The baseline assessment concludes that there is no tendency for any method to over or underestimate QMED with respect to catchment area. For estimating QMED, ReFH2-FEH99 performed the best overall in rural catchments. The FEH statistical method was found to outperform MacDonald and Fraser's method and to have a particular advantage in more permeable catchments. In urban catchments, error in QMED estimates from the FEH methods was not found to be related to urban extent, except in the most heavily urbanised case. The FEH statistical method was found to perform the best in urban catchments, although it may lead to overestimating QMED in small urban catchments with high average annual rainfall.

For return periods up to 500 years, the ReFH2-FEH99 method gave the smallest residuals, although all FEH methods were generally found to apply equally when estimating Q100 and QMED. The assessment was restricted to considering the set of as-rural small catchments classified as suitable for pooling procedures.

The baseline assessment concluded that there was scope for improving FEH methods in small, particularly urban catchments and this led to the analyses summarised in later sections of this report.

Further details are presented in **project report R2**, **project report R3** and **Vesuviano and others (2016)**.

6.1 Introduction

Flood estimation methods in the UK typically follow one of two approaches. The statistical index flood methodology links peak flow rates to measurable catchment and/or climate properties, while the rainfall-runoff approach models the flow response to a set of design inputs, including rainfall depth, duration, temporal distribution and antecedent catchment conditions. The choice of approach reflects the specifics of each individual application, for example, the size of the catchment and whether a design flood hydrograph is required. Some guidance on selecting the most appropriate method is given in FEH Volume 1 (Reed 1999) and the Environment Agency's Flood Estimation Guidelines (Environment Agency 2022).

In the assessment, several variants of the current FEH statistical and rainfall-runoff methods were tested (Note: This comparison was carried out at an early stage of the project and the analysis predates the release of ReFH 2.2 (Wallingford HydroSolutions 2016)). During phase 1 of this project, older methods such as IH124 (Marshall and Bayliss 1994) and ADAS 345 (ADAS 1982) were found to be inferior to current FEH methods (Environment Agency 2012), so were not considered again here. MacDonald and Fraser (2013) published an alternative QMED equation to the one in the current FEH statistical methods, and this equation was included in the comparison as it is specifically calibrated to small UK catchment data.

6.2 Summary of existing methods

6.2.1 Revitalised flood hydrograph method (ReFH1 and ReFH2)

The revitalised flood hydrograph (ReFH) method (Kjeldsen 2007) is a lumped, conceptual, event-based method for generating design flood hydrographs from design storm inputs. The model combines a loss component, unit hydrograph-based routing component and baseflow component. ReFH1 was calibrated using the FEH99 rainfall depth-duration-frequency (DDF) model (Faulkner 1999), and parameter estimation equations, using FEH catchment descriptors, allowing the method to be applied to ungauged sites. Collaborative research by Wallingford HydroSolutions (WHS) and the Centre for Ecology & Hydrology (CEH) led to the development of an upgraded version known as ReFH2 (Wallingford HydroSolutions 2016a). Design hydrographs from ReFH2 at the time of this study could be generated from either the FEH99 rainfall DDF model (Faulkner 1999) or the later FEH13 rainfall model (Stewart and others, 2013).

At the time of the baseline assessment, the FEH13 rainfall model and associated recalibration of the ReFH2 design package had not been released and therefore the baseline assessment considered ReFH1 used together with the FEH99 design package for ReFH2. The improvements for the application of ReFH2 developed within this project used the new ReFH2-FEH13 design package (Wallingford HydroSolutions 2016a) and therefore in the comparison of new methods both ReFH2 design packages are considered.

The development of ReFH2 has specifically addressed some of the issues that have been identified with ReFH1 (Faulkner and Barber 2009), particularly the performance of the method in urban catchments and permeable catchments. Additionally, a framework for including the impact of urbanisation explicitly is incorporated in ReFH2, following Kjeldsen and others (2013). Percentage runoff in ReFH2 is defined as a weighted sum of the contributions from the rural and urban parts of the catchment, with percentage runoff from the rural fraction estimated as in ReFH1. Runoff from the urban part of the catchment is further divided into that resulting from rain falling on pervious and impervious surfaces, with impervious surfaces assumed to have a constant runoff coefficient, following Packman (1980). The total net urban runoff is routed by convolution with a separate ‘urban’ unit hydrograph for which a shorter time-to-peak can be specified.

The ReFH2-FEH13 design package dispenses with the need for a parameter, the alpha parameter, required to ensure a correspondence of the T-year rainfall event with the corresponding T-year flow event. Although its formulation was revised for the ReFH2-FEH99 design package, the need for the alpha parameter was a hydrologically unattractive facet of the ReFH1 and ReFH2-FEH 99 design packages. Furthermore, because T-year estimates from the corresponding statistical method were used to identify values for alpha, the two approaches (rainfall-runoff and statistical) were not independent of one another.

6.2.2 FEH statistical methods

Estimating flood peaks requires an index flood and a growth curve to be estimated separately. The original FEH statistical methods (Robson and Reed 1999) were revised by Kjeldsen and others (2008) and the revised methods were adopted as the standard index-flood method, used to estimate catchment flood peaks for a range of areas and return periods. It is implemented in the WINFAP software package (Wallingford HydroSolutions 2016b).

Index flood

The index flood, defined as QMED, the median annual maximum flood, is estimated either from annual maximum peak flow data (AMAX) or from catchment descriptors. The most up-to-date version of the catchment descriptor equation as published in Kjeldsen and others (2008) is shown in Equation 17:

Equation 17 – Catchment descriptor equation

$$\mathrm{QMED_{CD}} = 8.3062 AREA^{0.8510} 0.1536^{\frac{1000}{SAAR}} FARL^{3.4451} 0.0460^{BFIHOST^2}$$

AREA is catchment area (km^2), SAAR is standard average annual rainfall (mm), FARL is the FEH index of attenuation due to lakes and reservoirs and BFIHOST is baseflow index derived from the HOST soil classification. The factorial standard error of this equation is 1.431.

Donor transfer

The QMED estimate derived from Equation 17 can be adjusted using a gauged QMED estimate from a nearby gauging station using donor transfer. Current guidance recommends using the closest donor. In practice, however, more flexible approaches are often followed (Environment Agency 2022).

Kjeldsen and others (2014) propose a modification to allow donor transfer using the n closest gauged sites. Typically, using six donors was found to be an optimal trade-off between the volume and relevance of information provided to the estimation procedure. Multiple donor transfer has not been widely adopted.

In this study, the improved (2008) FEH statistical method was tested with and without donor transfer, recognising that donor transfer is frequently not applied in small catchments.

Urban adjustment

Flood frequency is known to be affected by the level of urbanisation in a catchment. Therefore, QMED in ungauged urban catchments should also be adjusted for urbanisation as follows: $QMED = UAF \times QMED_{RURAL}$. UAF is an urban adjustment factor calculated from catchment descriptors.

Growth curve

The growth curve (z_T) is a dimensionless relationship that expresses QT over QMED, where QT is the T-year flood peak: $QT = z_T \times QMED$

This is parameterised by identifying a ‘pooling-group’, a set of gauged catchments that is similar to the subject site based on the catchment descriptors AREA, SAAR, FARL and FPEXT. L-moment ratios for each site in the group are pooled to form a single set of L-moments typical of the catchment of interest and adjusted if the target catchment is urban. An appropriate statistical distribution is chosen to compute the growth curve from the pooled L-moments: typically, the generalised logistic (GLO) distribution in the UK. QT flood peak estimates are found by multiplying the estimated QMED with the value of the growth curve corresponding to a probability of exceedance ($1 - 1/T$).

Enhanced single-site analysis

If gauged AMAX data are available at the site of interest, then enhanced single-site analysis can be used. This provides a framework to combine gauged data at the site of interest with gauged data from other sites, in order to create a larger data set suitable for estimating rarer floods. The index flood is derived purely from the gauged series at the site of interest, but the pooling-group also includes AMAX from other hydrologically similar sites. L-moments at the site of interest receive enhanced weighting.

6.2.3 MacDonald and Fraser’s QMED equation

MacDonald and Fraser (2013) published an alternative equation for the median annual flood in small catchments, developed with the specific aim of reducing the error in QMED estimates relative to the current FEH statistical method for catchments between 0.5 and 25 km^2 in area. This is shown in Equation 18:

Equation 18 - Alternative equation for the median annual flood in small catchments

$$QMED = 6.120 AREA^{0.758} 0.288^{\frac{1000}{SAAR}} 0.042^{BFIHOST^2}$$

Model development used a set of 104 essentially rural ($URBEXT_{2000} < 0.03$) and 31 more urbanised catchments. However, the equation does not account for differing levels of urbanisation, and the authors recommend that their equation is used as published for both urban and rural catchments. The authors did not publish any corresponding procedure for generating growth curves or for donor transfer. Therefore, this method was tested at QMED only.

6.3 Outcomes of the baseline assessment

The baseline assessment is presented in detail in project report R2 and only a summary is provided here. The methods assessed were:

- the FEH statistical method (Kjeldsen and others, 2008), with the updated urbanisation adjustment procedure (Kjeldsen 2010) and no donor transfer
- the FEH statistical method (Kjeldsen and others, 2008), with the updated urbanisation adjustment procedure and donor transfer from one site
- the FEH statistical method, with the updated urbanisation adjustment procedure and donor transfer from six sites (Kjeldsen and others, 2014)
- MacDonald and Fraser's 'improved method for estimating the median annual flood for small ungauged catchments in the United Kingdom' (MacDonald & Fraser 2013) - donor transfer and urban adjustment are not implemented
- the revitalised flood hydrograph (ReFH1) method (Kjeldsen 2007)
- the revitalised flood hydrograph (ReFH2) method (Kjeldsen and others, 2013; Wallingford HydroSolutions 2016a), with design event inputs from the FEH99 rainfall depth-duration-frequency (DDF) model (Faulkner 1999)

The FEH13 rainfall model had not yet been integrated with ReFH2 when this assessment was carried out. Later research, presented in Section 3 of this report, suggests that the performance of ReFH2 with FEH13 rainfalls improves upon that of ReFH2 with FEH99 rainfalls for both rural and urban catchments for return periods of two to 1,000 years.

Enhanced single-site values were used as the target against which performance was assessed, recognising that these are modelled estimates, but estimates that maximise the use of the at-site gauged AMAX data. The baseline assessment differentiated between as-rural catchments and catchments potentially influenced by urbanisation based upon the 'essentially rural' $URBEXT_{2000}$ threshold of 0.03 (Bayliss and others, 2006). Catchments with $URBEXT_{2000} < 0.03$ are therefore 'essentially rural', catchments with $URBEXT_{2000} \geq 0.15$ are 'heavily urbanised' and catchments with intermediate $URBEXT_{2000}$ values are 'moderately urbanised'. 'Heavily urbanised' and 'moderately urbanised' catchments together were termed 'urbanised', with no prefix. This is a stringent definition of urbanisation and the later analysis presented in report R6 would indicate that in small catchments the influence of urbanisation on the AMAX series within a catchment cannot be detected until the level of urbanisation exceeds an $URBEXT_{2000}$ value of 0.3.

The analysis was carried out using the 'high-quality' and 'extended' QMED catchment data sets and the data sets assessed as suitable for pooling. The FARL index is used to index catchments in which flood response is likely to be significantly attenuated by the presence of online lakes and the operation of online reservoirs. Catchments with a low FARL value were excluded from the statistical analyses as ReFH does not have a model structure for directly modelling these water features.

Performance was assessed via graphical analysis and summary statistics of model logarithmic residuals. The assessment considered both bias and unexplained variance (as estimated using the factorial standard error, fse) and assessed the evidence for any correlation of model residuals and catchment descriptors. The analysis of essentially rural catchments in the ‘extended’ data set produced slightly surprising results in that most values of the error statistics considered were lower than for the ‘high-quality’ data set. For this reason, subsequent work on the development of new flood estimation methods has analysed the ‘extended’ datasets.

The baseline assessment concluded that for QMED estimation in rural catchments:

- there is no tendency for any method to over or underestimate with respect to catchment area
- the strongest performance overall is given by ReFH2-FEH99, closely followed by the FEH statistical method
- ReFH2-FEH99 offers a distinct improvement in performance over ReFH1, particularly in more permeable catchments
- the FEH statistical method outperforms that of MacDonald and Fraser
- the FEH statistical method has a particular advantage in more permeable catchments
- using donor transfer was shown to marginally reduce bias

The assessment of QMED estimation in urbanised catchments demonstrated that:

- the FEH methods (that is, all but MacDonald and Fraser’s method) do not show a trend or relationship between error and $URBEXT_{2000}$ for catchments other than for the very heavily urbanised case
- ReFH2 performs better than ReFH1 in urbanised catchments
- overall, the FEH statistical method performs most strongly for QMED estimation in slightly to heavily urbanised catchments - however, the FEH statistical method may overestimate QMED in small urban catchments with high average annual rainfall (SAAR > 800 mm)
- all methods tend to underestimate QMED in very heavily urbanised catchments, severely so in extremely-urbanised catchments

Considering the assessment of the performance of the methods for estimating peak flows for return periods ranging between 100 and 1,000 years, the assessment for the as-rural catchment set concluded that:

- up to return periods of 500 years, ReFH2-FEH99 gave the lowest unexplained variance

- for the FEH statistical method, mean difference in ln(QT) does not vary noticeably with return period
- on average, ReFH2-FEH99 tended to underestimate rarer flood peaks in small catchments, while the FEH statistical method tended to overestimate rarer flood peaks in small catchments
- ReFH2-FEH99 improves greatly upon ReFH1. ReFH1 should never be used for return periods over 150 years as it can severely overestimate peak flows for longer return periods
- there was no dependence between method residuals and AREA, and the unexplained variance only increased slightly with increasing return period (noting that as return period increased the benchmark estimates are increasingly dominated by modelled outcomes)

The baseline assessment for longer return period events predated the development of the WINFAP4 procedures for applying the enhanced single-site method in urbanised catchments. Therefore, the assessment was restricted to considering the set of as-rural catchments classified as suitable for pooling procedures.

The baseline assessment concluded that there was scope for seeking improved statistical methods for estimating flood peaks in small catchments and proposed the following:

- development of a revised QMED equation for small catchments (< 25 km^2)
- development of a revised pooling procedure for small catchments (< 25 km^2)
- further refinement of the design inputs to the ReFH2 method for small catchments and plots
- analysis of hydrograph shape
- development of a free precautionary screening tool for plot-scale areas

These developments are reported in summary in the following sections of this report and the relevant project reports (R4, R5, R6 and R7).

7. Exploring new QMED estimation methods

This section summarises the development of several alternative methods for estimating QMED in small ungauged catchments. The analysis used the small catchment data set described in Section 4 to consider 3 general options for reducing uncertainty in estimating the index flood in small catchments:

- **Option 1** - recalibration of the FEH catchment descriptor equation using a data set of small catchments only to provide a ‘retuned’ QMED equation (Equation 20)
- **Option 2** - development of a new QMED regression equation, based on other catchment descriptors that are found to explain more variation in the observed QMED in small catchments
- **Option 3** - development of a new QMED equation based on regression as above, but with consideration given to using flow statistics together with catchment descriptors - these flow statistics require some gauging but can be estimated within weeks or months using equipment that is not accurate up to QMED

The analysis found that both the retuned index flood equation (option 1) and a new small catchment equation (option 2) offer improvements in terms of uncertainty in QMED. The new regression equation (option 2) is similar in form to option 1, relying on some measure of catchment area, rainfall and gridded soil properties. However, the improvement offered by option 2 over option 1 is considered too small to justify a complete overhaul of the model structure. The gauged flow equation (option 3) provides the best model fit to observed median annual flows. However, the smaller number of catchments for which flow statistics were obtained (46) means that this regression equation cannot be safely generalised to all small catchments.

Subsequent work to evaluate the performance of the retuned QMED equation concluded that there was little evidence to support using it over the existing FEH QMED equation of Kjeldsen and others (2008) (see Section 3).

The current FEH guidance on donor adjustment was reviewed using the small catchment data set and new guidance has been developed as follows:

1. donor transfer using one donor, selected purely by proximity and with the existing distance attenuation factor, is most beneficial in improving the estimate of QMED in small catchments
2. as a general principle, potential donors that are dissimilar to the site of interest in terms of catchment descriptors should not be discarded, as the model error in the QMED equation, which is what donor transfer is intended to correct, is not correlated with any catchment descriptor

Further details are presented in **project report R4**.

7.1 Background

Currently, the FEH statistical method is widely used and recommended for estimating the median annual flood (QMED) in any ungauged catchment in the UK. The method involves applying an equation based on FEH catchment descriptors as detailed in Kjeldsen and others (2008) and shown in Equation 19.

Equation 19 – Using FEH catchment descriptors to estimate QMED

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

This equation was calibrated using a large data set of catchments with an average area of several hundred km^2 and a maximum area of almost 10,000 km^2. Therefore, this project studied the feasibility of developing a QMED equation specifically to improve accuracy in small catchments.

7.2 Data and methods

Initially, a data set of 152 catchments, corresponding to the ‘high-quality’ QMED group in Table 38 minus one downgraded catchment, was used to provide data for a ‘retuned’ version of the FEH equation. In this, the form of the FEH equation was retained, including the same catchment descriptors in the same transformations. However, the coefficients were optimised for small catchments. The equation was retuned on a sub-group of 93 catchments under 25 km^2 as well as the full data set of 152 members. The coefficients were fitted according to almost the same method as the current FEH equation, accounting for spatial correlation in annual maxima and model error correlation (that is, fitting model residuals to follow a consistent spatial pattern, as in Kjeldsen and others, 2008). The only difference between this fitting method and that used for the current FEH equation was that the FEH modelled spatial correlation as the weighted sum of two distance-based exponential decays, while this study used only a single distance-based exponential decay to increase stability in the model fitting procedure.

Next, a small-catchment QMED model was built from scratch for the sub-group of 93 catchments under 25 km^2, to identify if any different catchment descriptors are more significant controls on QMED in small catchments. The equation was built according to the procedure in Section 4 of Kjeldsen and others (2008). The resulting equation was then refitted to a wider set of 132 small catchments with similar results.

In further work, gauged flow statistics, which can be obtained over a shorter monitoring period and to a higher accuracy than peak flows, were obtained for 46 small catchments under 25 km^2. An equation was built according to the same procedure, but with the option for the model-building procedure to select gauged flow statistics in addition to catchment descriptors.

7.3 Results

7.3.1 Retuned FEH QMED equation for small catchments

The retuned FEH equation for catchments under 25 km^2, derived from an analysis of the 93 ‘high-quality’ catchments that are under 25 km^2 in area is presented in Equation19:

Equation 20 – Retuned FEH QMED equation for small catchments

$$\mathrm{QMED} = 4.7260\,AREA^{0.8335}\,0.2763^{\left(\frac{1000}{SAAR}\right)}\,\mathrm{FARL}^{2.6266}\,0.0404^{BFIHOST^{2}}$$

$$\sigma^{2}_{\eta} = 0.2823 \qquad \phi = 3.0142$$

Model factorial standard error (fse) is 1.701, which is higher than that of the original (1999) and currently recommended (2008) FEH QMED equations. For comparison, a second retuned equation was fitted to data from the full set of 152 ‘high-quality’ catchments of area up to 40.9 km^2, although attention has focused on the equation based on smaller catchments. Further details are given in project report R4.

Figure 17 shows the influence of each catchment descriptor in the current FEH (2008) equation (grey), and the retuned equations using 93 catchments under 25 km^2 (orange) and 152 catchments up to 40.9 km^2 (blue).

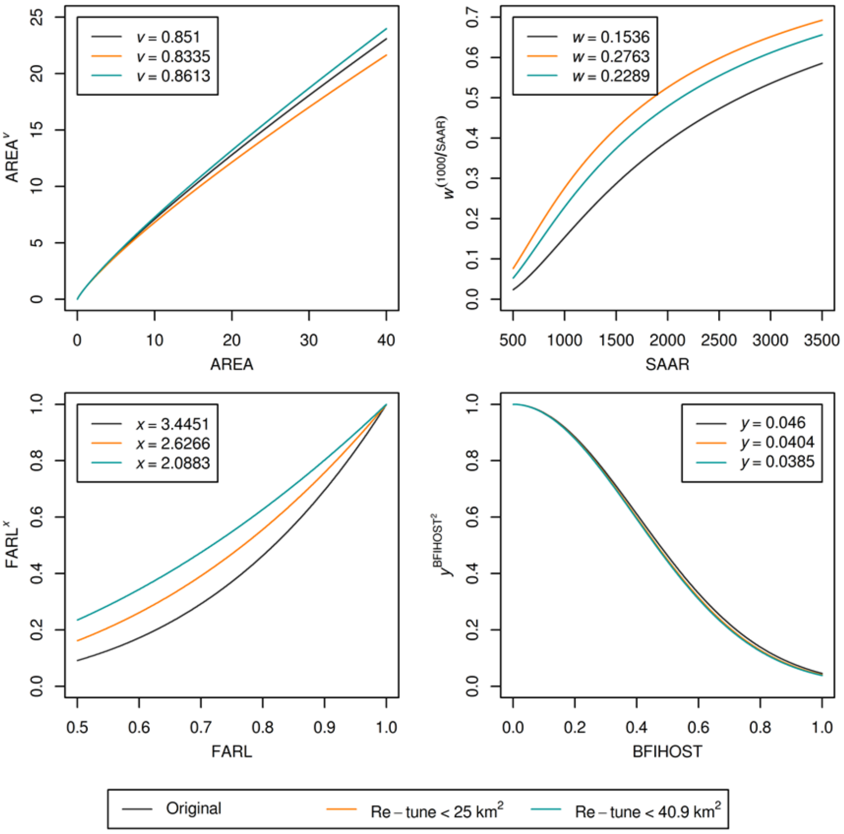

Figure 17 - Influence of catchment descriptors in original (grey) and QMED equation retuned with catchments up to 25 km^2 (orange) and 40.9 km^2 (blue)

Figure 18 plots QMED as estimated by the current FEH all-catchment and retuned QMED equations, showing that the retuned equations tend to underestimate the largest values of QMED. They also overestimate the lowest values, though generally to a lesser extent than the 2008 equation. All three equations tend to underestimate severely in heavily or extremely urbanised catchments. This indicates a need for further work on urban adjustment factors in the most severely urbanised catchments. Method performance is quantified numerically in Table 41.

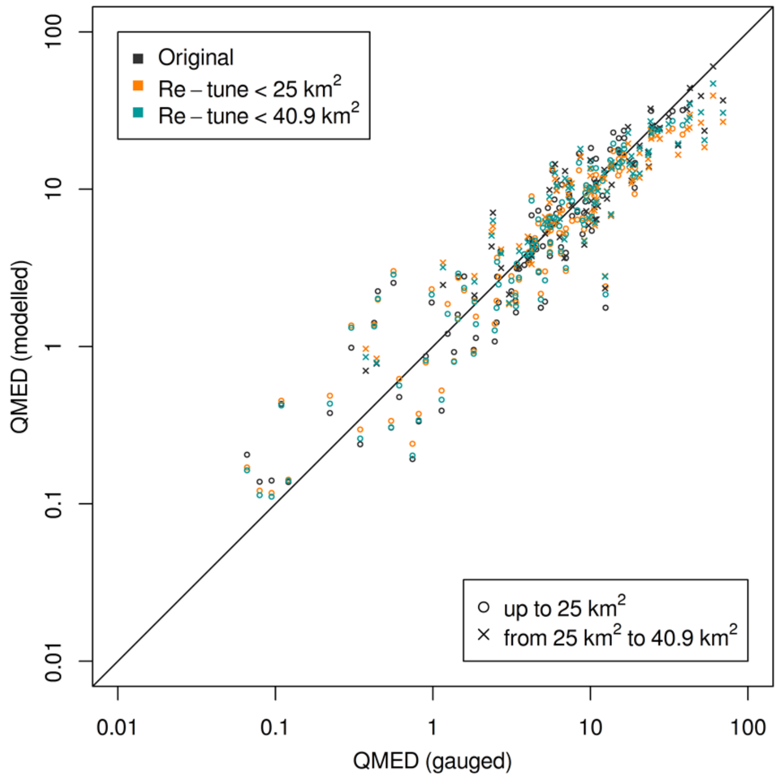

Figure 18 - Comparison of current (original) and retuned FEH statistical models for QMED

Table 41 - Performance of existing FEH all-catchment QMED equation compared with retuned versions for small catchments

Model variant	model fse exp(σ_η)	R^2	RMSE*	sample fse exp(s)
Original	1.431	0.8356	0.6116	1.843
Retuned, <25 km^2	1.701	0.8530	0.5596	1.744
Retuned, <40 km^2	1.670	0.8489	0.5671	1.757

Note: *Sum of squares of residuals divided by number of degrees of freedom (93 – 4 parameters – 1 = 88)

7.3.2 New QMED equation for small catchments

The potential new small catchment model for QMED was built using the 93 'high-quality' catchments under 25 km^2 in area using all FEH catchment descriptors except for those that cannot be calculated for every catchment (for example, URBLOC$_{2000}$ does not exist for rural catchments). By far the most important control on QMED was AREA, followed by

SPRHOST or BFIHOST, followed by rainfall descriptors (SAAR and RMED values of different durations). The newly developed equation is shown in Equation 21:

Equation 21 – New QMED equation for small catchments

$$\text{QMED} = 1.3274AREA^{0.8371}0.3516^{\left(\frac{100}{RMED13\text{-}2D}\right)}6.0604^{FARL^2}0.0436^{BFIHOST^2}$$

$$\sigma_{\eta}^{2} = 0.2549 \quad \phi = 3.0930$$

The new equation features AREA and BFIHOST in the same transformations as the existing FEH equation, 1-day RMED from the FEH13 rainfall model in the same transformation used by SAAR in the existing FEH equation, and FARL. This demonstrates that the same broad-scale catchment descriptors explain the variation in QMED in small catchments as in larger catchments. These broad-scale catchment descriptors cannot reflect local-scale influences on flood magnitude, such as modified drainage patterns. Verification on both the 152 catchments in the ‘high-quality’ QMED data set and the set of 132 catchments in the ‘extended’ data set with area less than 25 km^2 did not suggest that other catchment descriptors had been overlooked, as the order of importance (AREA, SPRHOST or BFIHOST, rainfall descriptor) was unchanged.

For comparison with Table 41, model factorial standard error for Equation 21 is 1.657, which is lower than that found for either of the retuned FEH QMED equations. However, further investigation provided evidence to suggest that this new model tends to slightly underestimate QMED on average in small catchments and the improvement in data fitting relative to the retuned equations was too marginal to justify a new model structure (see project report R4 for details).

7.3.3 Using gauged baseflow index and flow statistics

A model for QMED based on flow statistics was developed using a subset of 46 essentially rural catchments with suitable data. Including gauged flow statistics in the model building procedure resulted in a very different model form shown in Equation 22:

Equation 22 – A model for QMED in rural catchments using flow statistics

$$\text{QMED} = 9.9812DPLBAR^{0.3196}Q10^{0.6725}0.0503^{BFIHOST^2}$$

$$\sigma_{\eta}^{2} = 0.0693 \quad \varphi = 0.6577$$

The daily mean flow exceeded on 10% of days ($Q10$) was found to be the most important predictor of QMED, followed by BFIHOST or SPRHOST. AREA was found not to be important any longer, as it was incorporated somewhat into $Q10$ (see Figure 19). Including DPLBAR (mean drainage path length) provides information about flow paths that cannot be differentiated using the $Q10$ values alone.

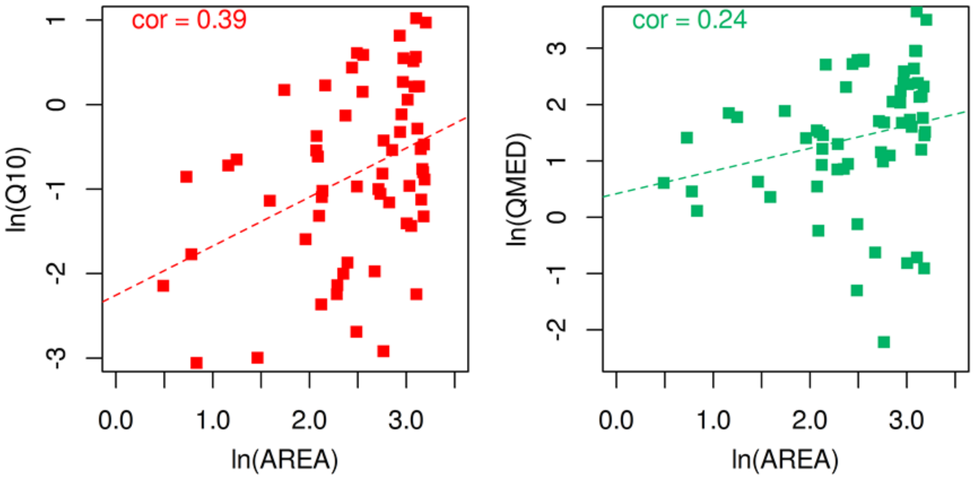

Figure 19 - Relationship between AREA, QMED and *Q*10

By comparison with WINFAP 4's QMED linking equation (Wallingford HydroSolutions 2016b), it is expected that percentiles of the flow duration curve higher than Q10 may be even more effective at predicting QMED. However, no flow percentiles higher than *Q*10 were readily available for this study. Despite the improved performance of the QMED equation built with *Q*10 (fse = 1.247), it was not taken forward as it is calibrated against just 46 catchments, and the flow statistics used could potentially include artificial influences. Further study of the relationships between urbanisation, artificial influences and the flow duration curve may allow this equation to be applied in urban catchments in future, thereby potentially increasing the applicability of the equation and the size of the calibration data set.

If reliable daily mean flow statistics are available for a small catchment of interest, it is recommended that the QMED linking equation (Equation 23) included in WINFAP 4 (Wallingford HydroSolutions 2016b) be used:

Equation 23 – QMED linking equation to calculate daily mean flow

$$\mathrm{QMED} = 1.762\,Q5_{DMF}^{\;0.866}(1+GRADQ5_{DMF})^{-0.775}DPSBAR^{0.265}0.2388^{BFI^2}$$

$GRADQ5_{DMF}$ is the gradient from $Q5_{DMF}$ to $Q10_{DMF}$ using a log-normal approximation and is calculated as shown in Equation 24:

Equation 24 – Calculating $GRADQ5_{DMF}$

$$GRADQ5_{DMF} = \frac{\log_{10} Q10_{DMF} - \log_{10} Q5_{DMF}}{0.365}$$

Note that BFI is the gauged base flow index – not BFIHOST.

7.4 Donor transfer

Donor transfer is a procedure whereby a statistical estimate of QMED at an ungauged site is refined using a gauged estimate at a gauged site. The FEH statistical model recommends using the geographically closest gauged site, measured between catchment centroids (not outlets), as the donor, and for the influence of the donor to be attenuated with increasing centroid-centroid distance. This is because the overarching pattern of QMED model residuals across the UK follows a smooth spatial pattern, so the ratio of gauged-QMED to equation-QMED is generally more similar for catchments with small centroid-centroid distance. More recent work (Kjeldsen and others, 2014) recommends using multiple donors, also selected by centroid-centroid distance, suggesting six donors as a trade-off between increased information and reduced marginal relevance of that information.

Spatial correlation between QMED residuals in small catchments is weaker than for UK catchments, which may be due to the increased centroid-centroid distances between small catchments in a smaller data set. In fact, almost zero spatial correlation is fitted in the retuned equation (Equation 20), so centroid-centroid distance cannot be recommended as the criterion for donor transfer. As the purpose of donor transfer is to ‘cancel’ the model residual at the site of interest, the best donors are those with similar model residuals. However, the eighteen scatter graphs in Figure 20, which plot model residual against various catchment descriptors for the small catchment data set, show that there is no relationship between model residual and any catchment descriptor. For the retuned equation, selecting any number of donors, either on centroid-centroid distance only or together with additional considerations based on AREA and SAAR, is more likely to worsen the estimate of QMED than it is to improve it (Tables 42 and 43). However, the typical errors with zero donors are already smaller than for the improved (2008) FEH equation with up to six donors.

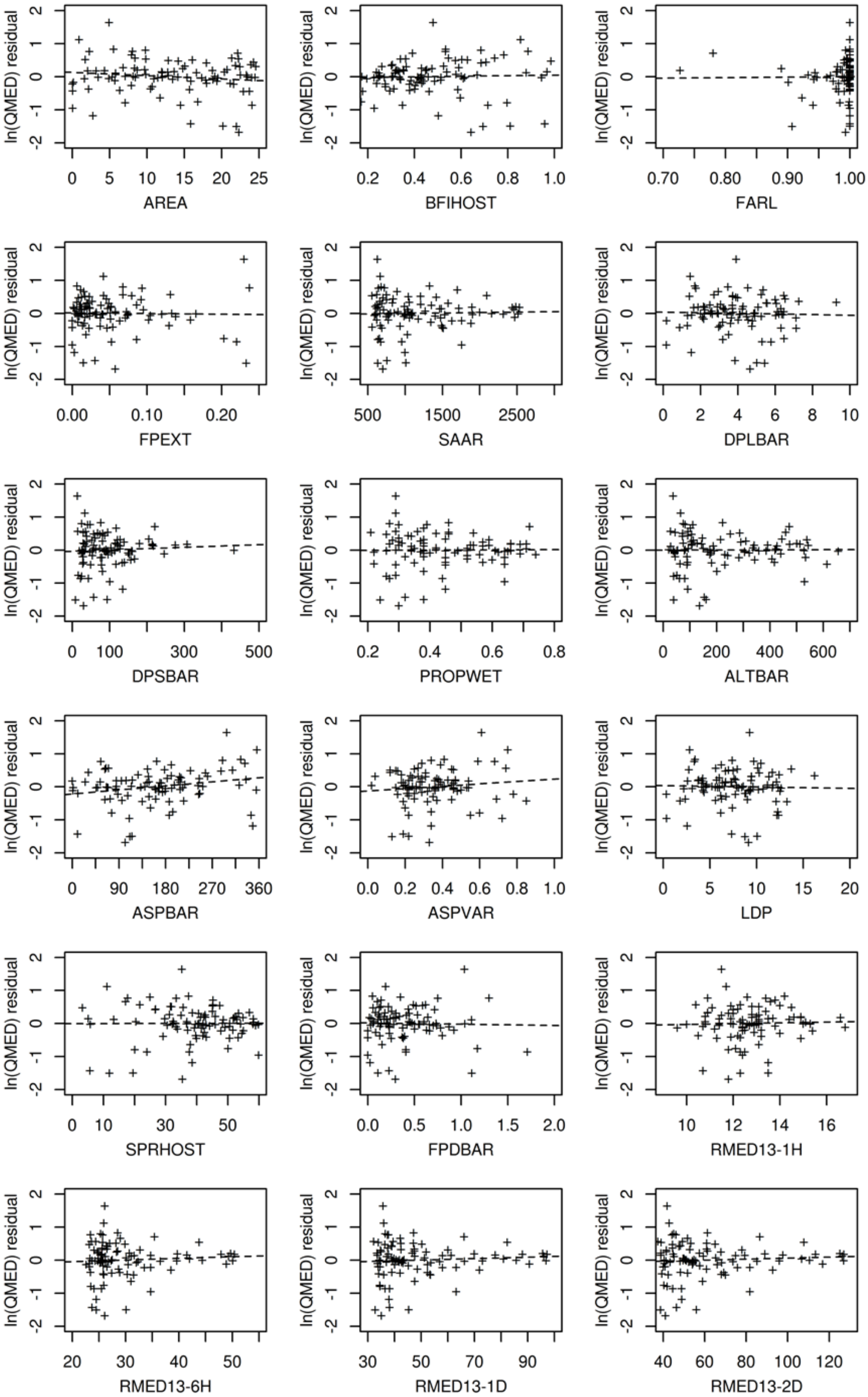

Figure 20 - Model residual vs catchment descriptors for retuned FEH statistical QMED equation with no donor transfer

Table 42 - Residuals in ln(QMED) estimates in relation to distance-only donor transfer (retuned FEH equation, 93 small catchments)

No. donors	No. residuals reduced (vs 0 donors)	No. residuals increased (vs 0 donors)	Mean ln-residual	Mean (ln-residual^2)
0	N/A	N/A	0.0025	0.2963
1	41	52	−0.0099	0.3042
2	42	51	−0.0134	0.3252
6	44	49	−0.0100	0.3250

Table 43 - Residuals in ln(QMED) estimates in relation to distance, AREA and SAAR-based donor transfer (retuned FEH equation, 93 small catchments)

No. donors	No. residuals reduced (vs 0 donors)	No. residuals increased (vs 0 donors)	Mean ln-residual	Mean (ln-residual^2)
0	N/A	N/A	0.0025	0.2963
1	41	51	0.0097	0.3347
2	42	49	0.0031	0.3495
6	38	53	0.0302	0.3428

For the improved (2008) FEH statistical QMED equation, model residuals can be shown to be slightly correlated with SAAR, ALTBAR, DPSBAR and PROPWET in small catchments, although these four descriptors are also correlated with each other. It is not recommended discarding potential donors whose catchment areas are very different from that of the target catchment, as no correlation is shown between model error and donor AREA. An illustrative test in which donor transfer based on centroid-centroid distance only was compared with donor transfer based on centroid-centroid distance and similarity in SAAR and AREA showed that ‘filtering’ potential donors by SAAR and AREA resulted in slightly lower mean ln-residuals in QMED and in reduced magnitudes of ln-residual in QMED at slightly more sites. However, these improvements were prevalent at sites where the model residual was already small before donor transfer.

The scatter graphs in Figure 21 compare the absolute model error after donor transfer when donors are selected by distance only (x-axis) or by a combination of distance, similarity in SAAR and similarity in AREA (y-axis). This demonstrates that "filtered" donor transfer (i.e. where potential donors are filtered by similarity in SAAR and AREA) was generally less helpful than distance only donor transfer in reducing model residuals at sites where the model residual was larger, i.e. where the improved (2008) FEH statistical method did not perform as well. Therefore, although there are some advantages to filtering potential donors for small catchment by AREA and SAAR, they are outweighed by disadvantages, particularly if the estimate of QMED given before donor transfer is poor (which will not be known if the catchment of interest is ungauged).

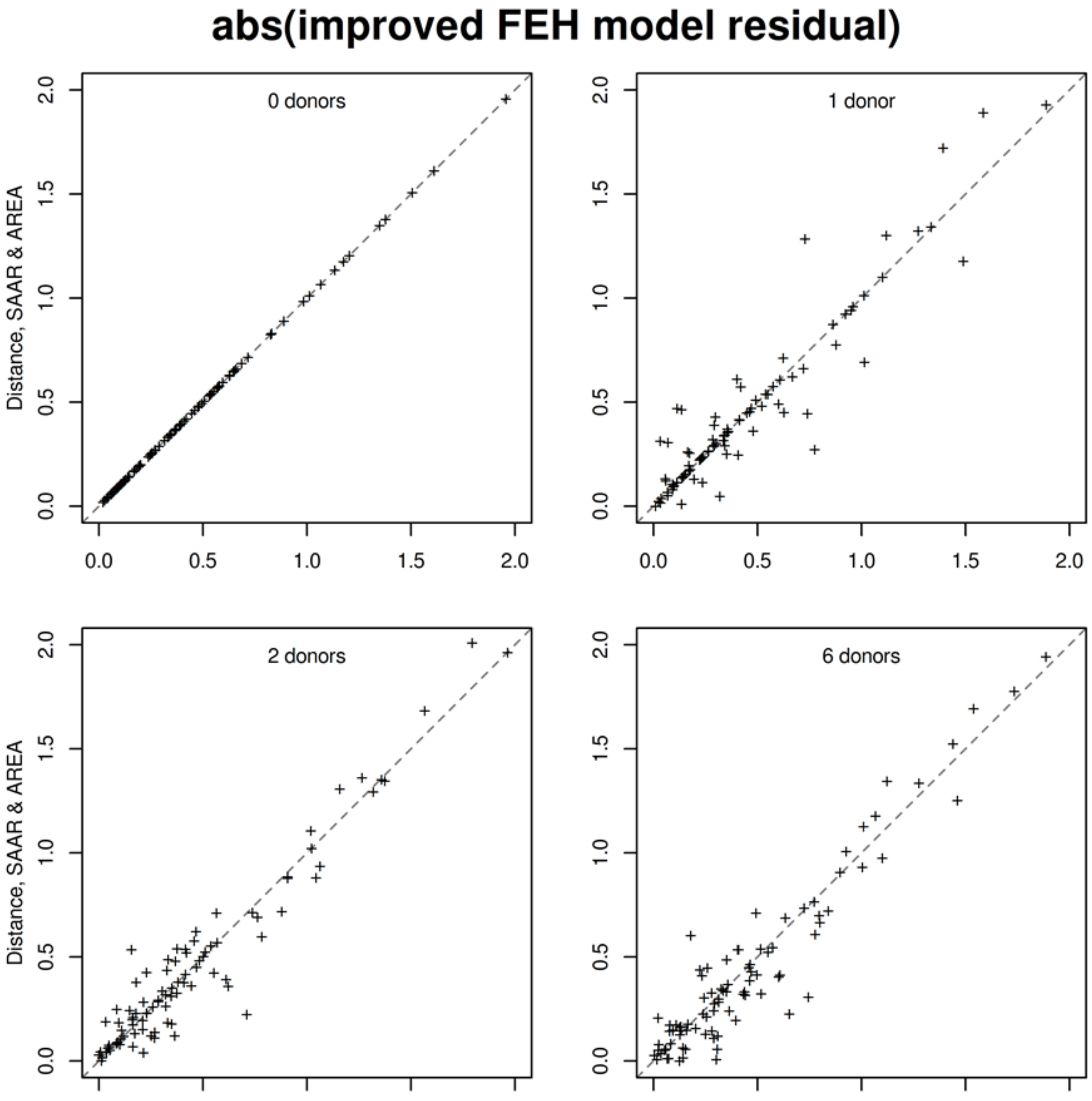

Figure 21 - Comparison of absolute model errors achieved by distance-only and filtered donor transfer (improved 2008 FEH statistical model, full NRFA database version 4.1, suitable for pooling)

7.5 Recommendations

For small catchments (that is, those under 25 km^2), using the existing all-catchment improved (2008) FEH equation is recommended over the retuned or new equations reported in this section. This is because work done subsequently in developing the re-tuned equation (detailed in Section 3 of this report) showed that the apparent improved performance relative to the 2008 equation was limited largely to catchments with questionable peak flow data quality.

For small catchments, using one donor selected by centroid-centroid distance **only** is recommended for refining QMED estimates made by the improved (2008) FEH statistical equation. Catchment characteristics should not be used to eliminate potential donors.

Based on exploratory studies, gauged flow percentiles are expected to be extremely useful in estimating QMED in small catchments. Further work should evaluate the performance of the QMED linking equation (Equation 23) in small catchments, and the potential for implementing this (or a similar) equation specifically in small catchments.

8. Developing a revised pooling procedure for small catchments

This section summarises the development of a new procedure for selecting pooling-groups for small catchments. The procedure was developed separately for each subset of catchments (under/over 25 km^2 and suitable for pooling/QMED estimation/not known), while the full set of 191 catchments with available annual maximum flow data (up to 40.9 km^2, not necessarily suitable for pooling) was used for verification. In summary:

- a new similarity distance measure (SDM), with less emphasis on catchment area, is used to assess the similarity between the catchment of interest and potential pooling-group members
- all other parts of the pooling procedure (weighting equations, target record length, default distribution) remain unchanged
- no restrictions should be placed on potential pooling-group members in terms of area; the new SDM already uses the AREA catchment descriptor to assess the suitability of potential pooling-group members

Further details are presented in **project report R5**.

8.1 Existing procedures

To estimate flood frequency curves where a site of interest is ungauged or has a short annual flood record, pooling-groups can be used to give improved estimates of L-moment ratios: L-CV and L-SKEW, which then are used to parameterise the appropriate flood frequency distribution: the generalised logistic distribution.

The improved 2008 FEH statistical pooling procedure (Kjeldsen and others, 2008) uses a similarity distance metric (SDM) to measure hydrological similarity through four catchment descriptors: AREA, SAAR, FARL and FPEXT, given in Equation 25:

Equation 25 – The improved 2008 FEH statistical pooling procedure

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

In this calculation, i and j refer to the target and a prospective pooling-group member. The denominator scales the difference by the standard deviation of that descriptor, so the preceding coefficients (3.2, 0.5, 0.1, 0.2) are the main weighting for each term.

Due to the high weighting on AREA and a lack of pooling-suitable gauged small catchments, small-catchment pooling-groups often consist mainly of other small catchments, which leads to a lack in variation in small-catchment growth factors. A new measure of hydrological similarity is developed specifically to allow for lower uncertainty in pooled estimates of long return period floods, and to increase variation between pooling-groups for small catchments, to improve differentiation between hydrologically-dissimilar small catchments.

8.2 Measuring similarity

In order to measure the efficiency of a new SDM and to compare it to the existing methods, a pooled uncertainty measure (PUM) as defined in Kjeldsen and others (2008) is used to quantify the performance of different pooling methods, through Equation 26:

Equation 26 – Using a pooled uncertainty measure to quantify the performance of different pooling methods

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

In this calculation, x_{Ti} is the at-site growth factor at the i'th site, x_{Ti}^{P} is the pooled growth factor. w_i are weights given by the following calculation (where n_i is the AMAX record length in years at site i):

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

The standard catchment descriptors as used for QMED estimation are available to use in selecting pooling-groups, along with four new descriptors:

1. ALIGN_V, a measure of north-south orientation:

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

   ALIGN_H, a measure of east-west orientation:

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

2. LONG = DPLBAR/AREA, a measure of elongation.
3. SHAPE = DPLBAR^2/AREA, a dimensionless version of LONG.

New SDMs were investigated by two methods centred on analysing correlations between the L-moments and functions of catchment descriptors. This procedure was performed separately for target sites in the following subgroups, always selecting pooling-groups from the whole pooling-suitable subset of the NRFA peak flow dataset (424 catchments of area from 1.63 to 4,587 km^2. NRFA database, version 4.1).

- pooling and QMED suitable with AREA < 25 km2
- pooling and QMED suitable with AREA ≥ 25 km2
- QMED suitable only with AREA < 25 km2
- QMED suitable only with AREA ≥ 25 km2
- non-assessed catchments (from MacDonald and Fraser 2013)

8.3 Visual selection of descriptors for SDM

An initial visual selection of descriptors to include in the SDM highlighted 1/SAAR, ln(DPSBAR), PROPWET and BFIHOST (illustrated in Figure 22) as the best to use in a two-term SDM, but none of the potential SDMs performed consistently better than the improved (2008) FEH pooling method across all subsets. See Table 44 for the pooling-suitable subset with AREA < 25 km^2. However, there was a general trend towards similarity in wetness over similarity in slope.

The strong performance of BFIHOST may be due to its strong correlation with PROPWET (cor = -0.55). For the larger (25 to 40.9 km^2) catchments, including BFIHOST and SPRHOST improved PUM values for both pooling- and QMED-suitable catchments, but did not achieve better performance than either the improved (2008) FEH pooling measure or an SDM containing PROPWET alone. This suggests that although there is room for improvement, a more systematic or statistical approach is required.

Table 44 - Relative performance of SDMs chosen by inspection on pooling-suitable sites with area less than 25 km^2

Descriptors (weights)	PUM T=20	PUM T=50	PUM T=100
1/SAAR (3.25), ln(DPSBAR) (1.0)	0.2790	0.3834	0.4652
PROPWET (1.0), ln(DPSBAR) (0)	0.2561	0.3538	0.4307
PROPWET (0), BFIHOST(1.0)	0.2556	0.3450	0.4145
FEH improved SDM	0.2570	0.3514	0.4252

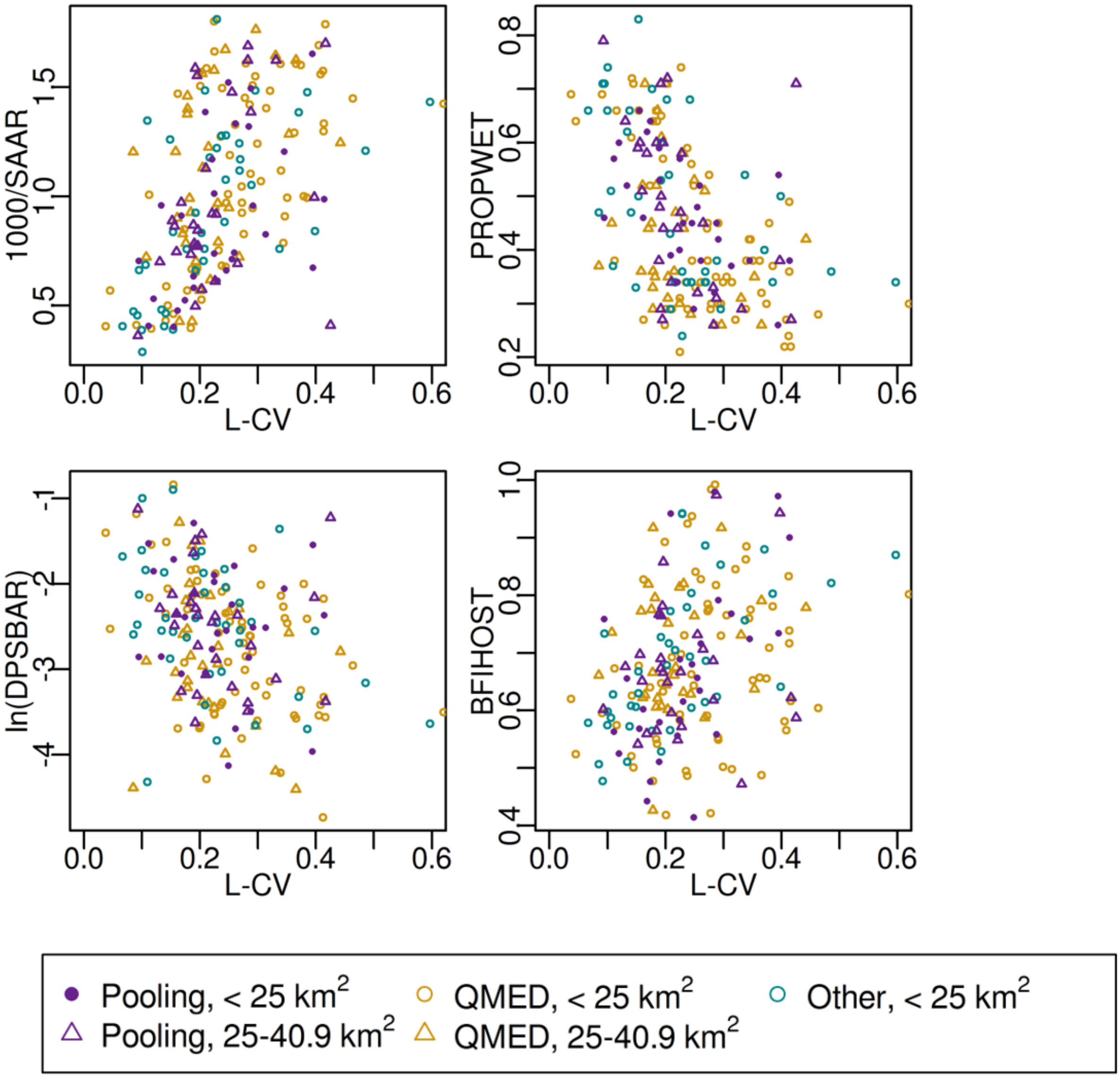

Figure 22 - Selected L-CV vs transformed catchment descriptors

The scatter graphs in Figure 22 show how, for each catchment, the L-CV of the annual maxima (on the x-axis) relates to four different catchment descriptors (on the y-axis).

8.4 Statistical selection of descriptors for SDM

Secondly, a more systematic statistical approach was taken to determining effective SDMs. Stepwise least-squares regression was used to identify the four descriptors explaining the most variation in L-moments: ln(L-CV) and L-SKEW, adding the descriptor which gave the biggest improvement in R^2. Table 45 summarises the sets of descriptors which performed best. In fitting to ln(L-CV), a high level of dissimilarity was observed between the descriptors selected for different subsets of the data, though functions of SAAR were consistently chosen as a key descriptor for ln(L-CV). SHAPE and LONG were also important in the smallest catchments, suggesting that scale becomes more of a consideration than geometry only in larger catchments. L-SKEW models were very varied, but this is consistent with the limited variance (8%) explained by the original FEH SDM (Robson and Reed 1999).

Table 45 - Catchment descriptors explaining most variation in ln(L-CV)

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

With this knowledge, a 2-parameter SDM was determined for each group by systematically testing all 2-parameter combinations with influence on either L-CV or L-SKEW, and applying a range of weighting pairs to each combination. This method, summarised in Table 46, showed that in all the smallest catchments, AREA or ln(AREA) was selected with another similarly weighted descriptor. Comparing the values of PUM within each group shows a small but consistent improvement using these new candidates for SDM.

Table 46 - Best statistically-selected two-parameter SDMs and corresponding PUMs

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	exp(*FARL*) (2.75), 1/*PROPWET* (1.0)	0.1588	0.2093	0.2497
QMED <25	*SAAR* (2.5), ln(*AREA*) (1.0)	0.2851	0.3918	0.4763
QMED >25	ln(*SAAR*) (5,75), exp($ALIGN_H$) (1.0)	0.1833	0.2524	0.3076
Other <25	$SPRHOST^2$ (1.25), *AREA* (1.0)	0.2930	0.3910	0.4659
All groups combined	ln(*AREA*) (1.25), *SAAR* (1.0)	0.2592	0.3508	0.4224

Comparing the SDM structures suggests an optimal form contains AREA and SAAR. A systematic analysis of various weighting schemes was applied to minimise PUM for T=20, 50 and 100 years. Across the whole set of 191 catchments, PUM was fairly insensitive, but for the pooling-suitable catchments with AREA < 25 km^2, there was a clearly optimal choice of even weighting giving PUM values of 0.249, 0.340 and 0.411 for T=20, 50, 100 respectively. The final form of the SDM is given in Equation 27:

Equation 27 – The final form of the new SDM

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

Two 3-parameter SDMs, including 1/PROPWET or exp(FARL) were also investigated but showed no improvement on the 2-parameter SDM.

Figures 23 and 24 illustrate the improved differentiation achieved by using the new SDM (Equation 27) for pooling in small catchments. These heatmaps show the amount of similarity: a value of 1 (dark red) shows that two catchments have identical pooling-groups, a value of 0 (white) shows that the two catchments have entirely disjoint pooling-groups. This figure focuses on just the 28 pooling-suitable catchments under 25 km^2, but shows that for the new SDM there is an overall lower mean similarity between different pooling-groups (0.271 vs 0.414). More white space on Figure 24 compared to Figure 23 indicates more different pooling-groups, and fewer of the darkest areas indicate the reduction in identical pooling-groups. This suggests that the new method greatly improves differentiation between catchment pooling-groups, allowing for better comparison.

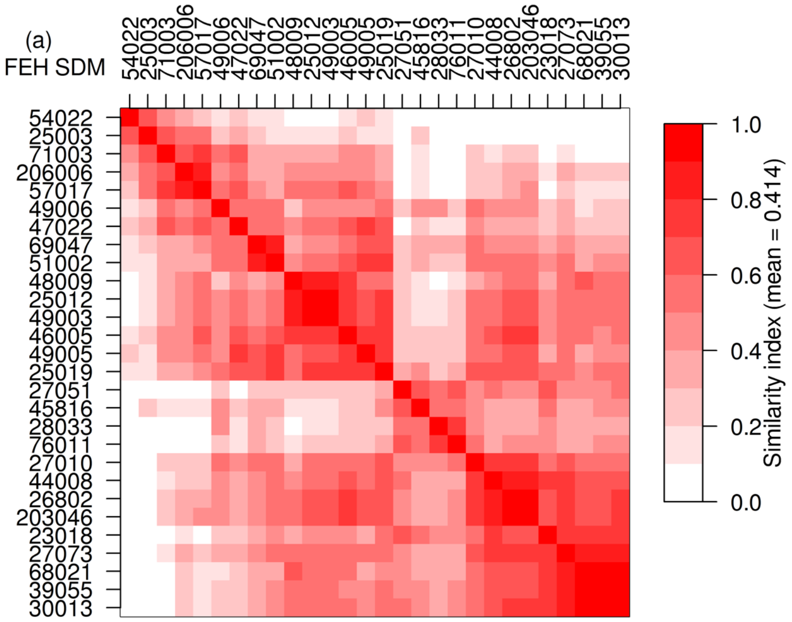

Figure 23 – FEH SDM (Equation 25) similarity heatmap for 28 pooling suitable catchments with AREA < 25 km2

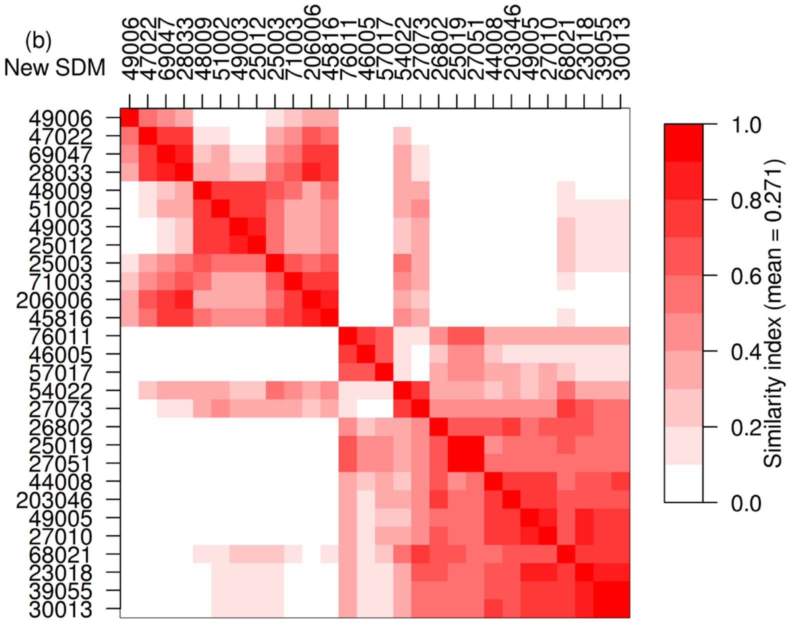

Figure 24 – New SDM (Equation 27) similarity heatmap for 28 pooling suitable catchments with AREA < 25 km2

8.5 Recommendations

It is recommended that for small catchments, the new SDM given in Equation 27 should be used to determine the most suitable catchments for a pooling-group analysis. Candidates should be taken from the whole pooling-suitable subset of the NRFA peak flow data set. For larger catchments (AREA > 40 km^2), the pre-existing improved (2008) FEH statistical method should still be applied. For catchments of size near to the small catchment threshold, analyses should be performed using both the existing and new SDM, and expert judgement exercised as to which pooling-group to use.

Regardless of the size of the target catchment, pooling-groups should be verified, checking for hydrological similarity, data quality and any discordant catchment (that is, presenting significantly different L-moment ratios from others in the pooling-group), and removing those with obvious and serious hydrological differences from the target and those with poor data quality. Discordant catchments should not be removed where the discordancy is not due to severe hydrological difference or poor data quality. Extra care should be taken when reviewing a pooling-group created using the new SDM, as it ignores some catchment descriptors that had no systematic effect in the data used to generate the measure but are nevertheless known to affect flood peaks (for example, FARL).

The change in the SDM is the only difference between the new small catchment and pre-existing improved (2008) FEH pooling procedures. As previously stated in the FEH literature, pooling-groups should be drawn from the pooling-suitable subset of the NRFA peak flow data set with the aim of having a total record length of 500 years for any return period of interest. This still applies to small catchments under the new procedure. Additionally, the equations used to calculate weighted means of L-moment ratios are unchanged from the improved (2008) FEH method, for both ungauged and enhanced single-site analyses, and the default distribution remains as the generalised logistic (GLO).

9. ReFH2: Estimating design hydrographs in small catchments

Design flood hydrographs provide important information for flood studies and complement statistical methods of estimating catchment peak flows. Hydrograph shape gives an indication of the full runoff response to an extreme rainfall event, which can be particularly important in reservoir storage and flood plain modelling. During the project, three separate analyses were carried out relating to estimating design hydrographs in small catchments and plots.

Firstly, the current recommendations for seasonal design inputs to the ReFH2 method, which are linked to the extent of catchment urbanisation, were reviewed. The implications of the analysis have been condensed into a set of rules for selecting when summer storms should be used within ReFH2, namely:

- if $URBEXT_{2000} \geq 0.3$ (that is, the catchment is very heavily urbanised), summer storms should be used with summer initial soil moisture, Cini
- if $URBEXT_{2000} \geq 0.15$ and $BFIHOST \geq 0.65$ and $SAAR < 800$ mm, summer storms and summer Cini should be used
- otherwise, winter storms and initial soil moisture should be used

The review suggests that the current summer storm profile is too peaked and recommends that estimating storm profiles is an area that requires further research across the full range of catchment scales.

Secondly, a review of the evidence for imposing a lower limit of catchment time-to-peak (Tp) of one hour in small catchments and plots was carried out. The results indicate that in small catchments (between 0.5 and 25 km^2) the lower Tp limit of one hour should be retained and that it is marginal as to whether the catchment Tp or plot-scale Tp equation should be used. In the case of estimating plot-scale runoff, the results suggest that it is appropriate to limit Tp to one hour as this will provide a conservative estimate of the allowable rate of discharge from a development site.

The final analysis compared two different approaches to estimating hydrograph shapes for design flood estimation: the ReFH2 rainfall-runoff method and the empirical median hydrograph (EMH) method, outlined by Archer and others, 2000. It was concluded that, within the limitations of sample size and the limitations of both methods, it is reasonable to conclude that the hydrograph shape predicted by ReFH2 is generally consistent with the shape of observed events, particularly in rural catchments.

Further details are presented in **project report R6**.

9.1 Introduction

The baseline assessment of methods (Section 6) suggested that improvements could be sought in the performance of ReFH2 in small urban catchments by reconsidering the choice of storm seasonality and re-evaluating the parameterisation of the ReFH2 urbanisation model.

In addition to the peak flow estimate, the form of an estimated design event hydrograph is important in both the hydraulic modelling of fluvial events and drainage design. The shape of a design event hydrograph is a function of the design hyetograph and the choice of rainfall-runoff model parameters.

The development of the ReFH design package was based on relationships between the parameter values obtained through calibration of the ReFH model using a representative set of catchments and the hydrological characteristics of those catchments. As the replication of hydrograph shape forms part of model calibration, then this will feed through into the design package equations for model parameters. However, in the design application the duration and storm profiles (in part determined by the estimate of Tp) will also strongly influence shape.

The original calibration of the ReFH model was carried out using rainfall and streamflow data with an hourly time step, and therefore there is a theoretical lower limit to the calibration of Tp of one hour. Based on this theoretical consideration and a relatively small sample of plot-scale data sets (see Section 10), a lower limit to the estimates of Tp of one hour is applied within the ReFH2 software. Section 9.4 explores whether this limit is appropriate and presents the evidence that this limit should be retained and is, in fact, invoked less frequently than commonly perceived.

Section 9.5 presents a comparison of the ReFH2-FEH13 hydrograph shapes with those derived empirically through an analysis of observed events for a relatively small set of small catchments. The purpose of this comparison is to test how representative the methods are: are the hydrograph shapes similar within the context of the uncertainties in both methods? Where the shapes are substantially different, reasons have been sought for those differences.

Returning to the seasonality of storm events, the recommendation on the release of ReFH2-FEH99 was to use winter storms in all catchments, albeit with caution in highly urbanised catchments. This recommendation was based on an analysis of model residuals for all urbanised catchments (irrespective of size) held in the NRFA peak flow database. Through this analysis recommendations for default parameters for the ReFH2 urbanisation model were also made.

Following the release of ReFH2-FEH13, a preliminary assessment of the performance of ReFH2-FEH13 confirmed this to also be the case when the FEH13 rainfall model is used.

The recommendation is to use ReFH2 with the FEH13 rainfall model as the performance of the model over all NRFA peak flow catchments is marginally improved over the performance observed with the FEH99 rainfall model. Furthermore, and most importantly, there is no requirement for the alpha parameter to ensure the correspondence of the T-year rainfall event and corresponding peak flow event. This is both hydrologically attractive and means that the application of ReFH2-FEH13 is entirely independent from the FEH statistical method other than in the assumption of a contributing catchment area. This is a valuable outcome when assessing alternative flood estimates within ungauged catchments to identify a best estimate for design.

The research summarised in this section therefore focused on improving the performance of ReFH2-FEH13 in small, urbanised catchments. Two aspects have been considered:

- section 9.2: storm seasonality within ReFH2 – when should a summer storm profile be used?
- section 9.3: parameterisation of the urban model - should the current default ReFH2 values be revised to reflect both new catchment information and use of summer storms?

The full detail is presented in the accompanying project report R6. The outcomes should be considered together with the wider evaluation of ReFH2-FEH13 presented in Section 3.

9.2 Storm seasonality within the ReFH design package

Annual maximum peak flow events within rural catchments tend to be associated with winter events. This is a consequence of low previous soil moisture deficits and high rainfall depths associated with winter depressions, particularly in the wetter west of the United Kingdom. In contrast, for urban catchments, in which substantial depths of runoff may be generated from impervious surfaces, the dominant flooding mechanism is believed to be associated with summer convective storms. Several observed rainfall depths generated by convective storms are recognised to be some of the highest on record. In larger and more rural catchments, these storms do not necessarily lead to the largest fluvial flood events as the storms tend to be of limited spatial extent and, on average, summer soil moisture deficits are higher than winter deficits, which are commonly negligible in all but the driest winters.

Project report R6 reviews the design storm hyetograph model used within ReFH to ascribe a winter or summer storm profile to the rainfall depth estimated from the rainfall depth-duration-frequency (DDF) model. The summer storm is significantly more peaked than the winter storm for a given duration.

To develop a recommendation on when a summer storm should be used, a review of flood seasonality and dependencies on urbanisation levels was carried out. The AMAX series for all NRFA peak flow catchments and the small catchments data set were analysed using directional, or circular statistics (Fisher 1993).

Figure 25 shows a map of UK flood seasonality based on the annual maxima for the small catchments data set and additionally, for context, all catchments in the NRFA peak flow database v4.1. Within the figure, the catchments are categorised by the degree of urbanisation (as represented by the $URBEXT_{2000}$ catchment descriptor).

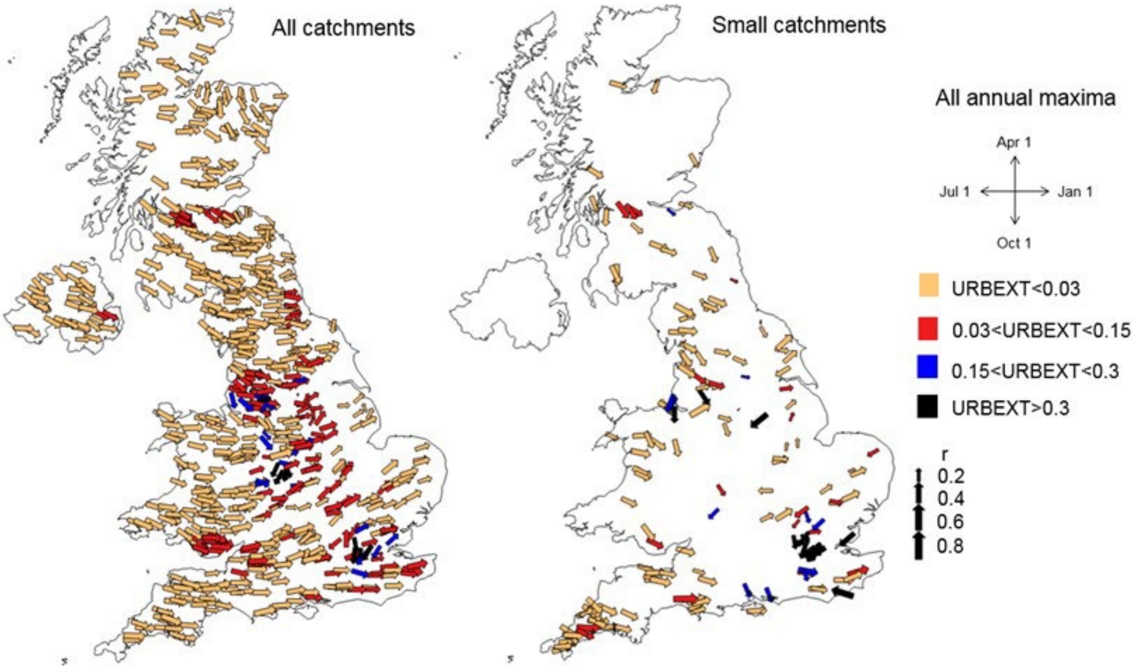

Figure 25 - Flood seasonality maps for all NRFA peak flows catchments (left side) and for the small catchments (right side), categorised by $URBEXT_{2000}$ value. Seasonality is calculated from all annual maxima

The direction and the size of each arrow represents the mean flood date and the concentration of the seasonal distribution (that is, the strength of the seasonal signal in the data). For predominantly rural catchments (that is, those below an $URBEXT_{2000}$ threshold of 0.15) the general pattern across all catchments is that:

- the annual maximum series is strongly dominated by winter floods across all rural catchments
- there is an indication that the mean seasonal signal migrates from early to late winter along a west to east gradient, except for north-east Scotland where the signal is towards early winter
- within small catchments this general pattern of winter floods in rural catchments is generally maintained, although the signal is weaker in the eastern side of England reflecting the balance between the weakening influence of frontal precipitation associated with Atlantic depressions, and the increased incidence of convective storms
- convective storms have a limited spatial extent but can be a source of extreme floods in small, generally more eastern rural catchments - the balance is such that in a small number of catchments the signal would appear to be weakly summer dominated - however, a more appropriate interpretation is that in catchments where the signal is weak, there is no strong seasonality in the flood regime

Considering the urbanised catchments (the blue and black arrows) the seasonality patterns are more complicated. However, the following key points can be explained:

- very heavily urbanised catchments ($URBEXT_{2000} \geq 0.3$) tend to be small catchments, as would be expected
- very heavily urbanised catchments ($URBEXT_{2000} \geq 0.3$) tend to experience summer floods
- the seasonality patterns are mixed in the heavily to very heavily urbanised class, with both winter and summer flood regimes evident - some of these differing patterns are strongly seasonal in some catchments and weakly seasonal in other catchments

To explore whether the observed seasonal patterns are different for the most extreme observed events, the analysis was repeated considering only the highest three annual maxima. This confirmed the general patterns observed for all maxima but with much more noise in the patterns. The main interpretation is that intense summer events are more prevalent among the highest annual maxima, and particularly so in the rain shadow to the east of the UK. However, the general conclusion is that in rural catchments winter storms still tend to dominate and in very heavily urbanised catchments summer events tend to dominate.

To explore these patterns further, and to develop guidelines for when summer events should be used in ReFH2, the results for all catchments (the combined set of the full NRFA peak flow data set plus the additional catchments from the small catchment data set) were categorised by catchment type: climate (SAAR), permeability (BFIHOST) and scale (AREA). For each typology index, catchments were classified by the extent of urbanisation and within each urbanisation class catchments were differentiated by seasonality, summarised as the percentage of summer and winter events respectively. This analysis did not differentiate on the strength of the seasonal signal, just that it is present. The classification outcomes are explored in full within project report R6, but based on this classification it can be concluded that:

- seasonality is independent of catchment scale, although high levels of urbanisation tend to be associated with small catchments, as would be expected
- winter storms dominate flood regimes in predominantly rural catchments (URBEXT2000 < 0.15) for all catchment types
- considering the ‘very heavily urbanised’ class (URBEXT2000 ≥ 0.30) summer storms dominate the flood regime of catchments in this class
- Within the 0.15 ≤ URBEXT2000 < 0.30 interval, if the SAAR value is less than 800 mm and the catchment is permeable (BFIHOST ≥ 0.65), then summer floods dominate, otherwise the dominant flood season is still winter.

These observations can be condensed into a set of rules for selecting when summer storms should be used within ReFH2:

- summer storms should be used if $URBEXT_{2000} \geq 0.3$ or
  if $URBEXT_{2000} \geq 0.15$ and BFIHOST ≥ 0.65 and SAAR < 800 mm

- winter storms should be used otherwise
- these rules are scale independent - therefore, they apply to all catchments, not just small catchments

9.3 The ReFH2 urbanisation model

The revision of the small catchments application of the ReFH2 urbanisation model in practice applies to all catchments regardless of area. The revisions comprise:

- developing a summer Cini model for use when summer storm profiles are recommended (see previous sub-section)
- a review and revision of the default parameters for the ReFH2 urbanisation model

9.3.1 The summer C_{ini} model

The FEH13 rainfall model was recommended for use with ReFH2 at the time of study and therefore the C_{ini} model for the ReFH2-FEH13 design package was extended to estimate summer design C_{ini} values as well as winter values. The design estimates of C_{ini} are a function of BFIHOST only when the FEH13 rainfall model is used. The C_{ini} design equation was optimised under the assumption of a winter storm profile using rural catchments and matching observed and design package estimates of QMED for these catchments (Wallingford HydroSolutions 2016a).

To explore whether the application of summer storms should be accompanied by a summer C_{ini} design estimate, this calibration approach was repeated using an expanded set of rural catchments to include the additional small rural catchments. Two scenarios were evaluated; a summer seasonal correction factor (SCF) used with the 50% summer storm profile and repeated using the 75% winter storm profile. The rationale for evaluating the two storm profiles reflects a concern that the summer profile is too peaked, and this is supported by a review of the origins of the use of this profile together with the original FSR DDF model (see project report R6). A summer BF_0 was used for both scenarios.

The catchment level required C_{ini} values are plotted as a function of BFIHOST for the winter and the two summer storm scenarios in Figure 26. That is, these are the C_{ini}/C_{max} values required to reconcile the modelled estimates of QMED with the data-based estimates of QMED under each scenario. The ReFH2-FEH13 winter C_{ini} model is included for reference.

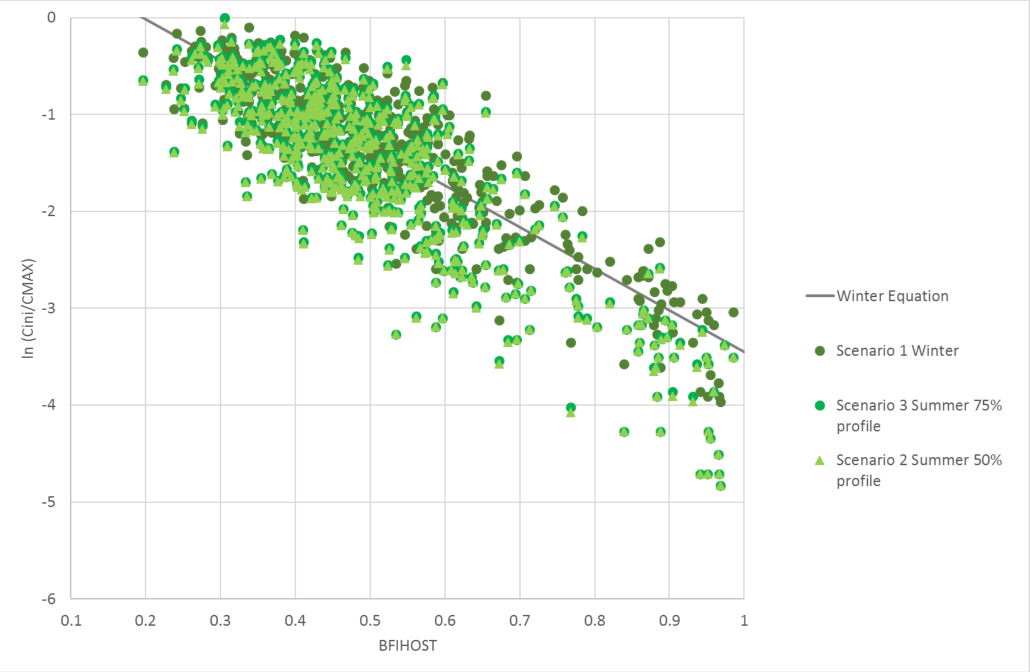

Figure 26 - Relationships between the calibrated values of C_{ini}/C_{max} for seasonal storms and BFIHOST

The SCF values are a function of both SAAR and duration. Figure 26 demonstrates that significantly smaller C_{ini} values are also required in permeable catchments (which also tend to be low SAAR catchments).

The relationships between the ratio of the optimal summer C_{iniS} to the design winter C_{iniW} and catchment descriptors were explored, and the best relationships identified were with the square root of the ratio of BFIHOST to SAAR. Catchment scale was not a useful explanatory variable.

Figure 27 presents these relationships for the full summer design model and winter profile design model. The form of the relationships is described by Equation 28 with the gradients, intercepts and measures of fit summarised in Table 47.

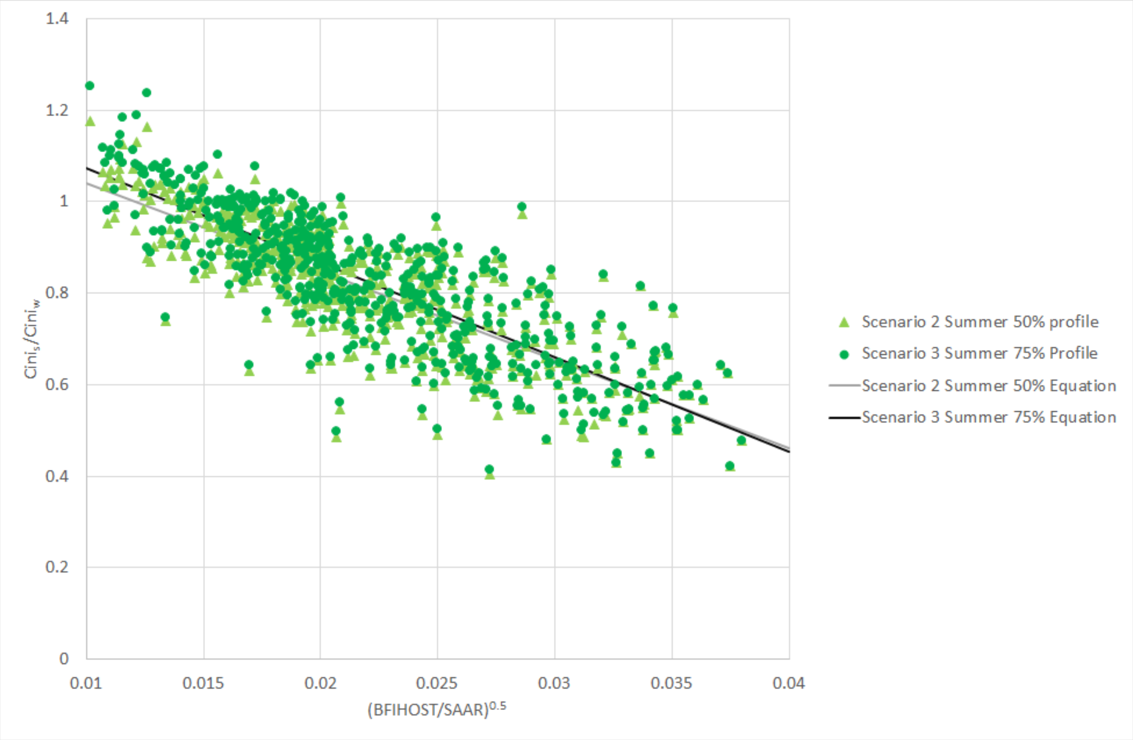

Figure 27 - The relationships between summer and winter Cini and the ratio of BFIHOST to SAAR for summer storms with summer profiles and summer storms with winter profiles

Equation 28 – Modelled relationship between summer *C_{ini}*, winter *C_{ini}*, *BFIHOST* and *SAAR*

$$\frac{C_{ini,s}}{C_{ini,w}} = m\left(\frac{BFIHOST}{SAAR}\right)^{0.5} + c$$

Table 47 - Model parameters and fit statistics for estimating summer Cini from the design winter Cini

Scenario	*m*	*c*	R^2	f.s.e
Summer: 75% winter profile	-19.33	1.24	0.67	1.16
Summer: 50% summer profile	-20.69	1.28	0.68	1.12

9.3.2 A review and revision of the default parameters for the ReFH2 urbanisation model

For the ReFH2 urbanisation model, the runoff/loss model is subdivided into rural and urban terms, where the percentage runoff (PR) is given by the calculation shown in Equation 29:

Equation 29 – ReFH2 urban and impermeable percentage runoff (PR)

$$PR_{urban} = (1 - 1.567IF \times URBEXT_{2000})PR_{rural} + (1.567IF \times URBEXT_{2000})PR_{imp}$$

$$PR_{imp} = 100 \times IRF \times D$$

PR_{rural} comes straight from the ReFH2 loss model, D is the total event rainfall depth, IF is the imperviousness factor and IRF the impervious runoff factor. For the routing and baseflow models, a Tp scaling factor is applied to urban compartments.

Default values are recommended for these three factors. To determine whether the default values should still be recommended, the ReFH2 model was run using the FEH13 rainfall model for all urbanised catchments with $UBBEXT_{2000} \geq 0.15$ and values of IF and Tp scaling factor were optimised holding IRF at the accepted value of 0.7. These were optimised through minimising ReFH2 residuals for QMED, using the above summer/winter recommendations. This analysis considered two classes of urbanisation:
$0.15 \leq URBEXT_{2000} < 0.3$ and $URBEXT_{2000} \geq 0.3$. The choice of these class boundaries was based on the existing seasonality rules, that is, 0.3 is the threshold at which the seasonality analysis suggests that the largest flood events tend to be summer events in all catchments, and in the interval $0.15 \leq URBEXT_{2000} < 0.3$ the large events in permeable catchments tend to be summer events.

The analysis considered a scenario of a winter storm in all catchments and two mixed winter-summer scenarios using the SCF and the two storm profiles for catchments for which the seasonality analysis suggested that a summer event was appropriate. A baseline run of winter rural conditions (setting $URBEXT_{2000} = 0$) was also run as a control.

The analysis showed that in catchments in the class interval $0.15 \leq URBEXT_{2000} < 0.3$ the winter as-rural estimates were unbiased and using the urbanised model runs introduced a tendency to overestimate slightly, irrespective of the choice of IF and the Tp multiplier. For catchments in which $URBEXT_{2000} \geq 0.3$, the minimum bias solution was found for IF = 0.3 and Tp multiplier = 0.5, therefore confirming the current defaults for ReFH2. However, the results obtained using the 75% winter profile were slightly less biased than the results obtained using the 50% summer profile. This suggests that the summer storm profile is too peaked. Project report R6 includes recommendations for further research on appropriate storm profiles. Based on this analysis, the following recommendations are made.

For catchment application:

- if $URBEXT_{2000}$ is ≥ 0.3:
    - a summer storm is to be used in all catchments with either the 75% winter or 50% summer profile - the results would suggest that the 75% winter profile is marginally better but either will suffice
    - a value of IF = 0.3 and a Tp factor of 0.5 are to be used with urban model - the IF value may be revised in application based upon detailed survey information
- if $URBEXT_{2000}$ is < 0.15

    - the catchment can be treated as a rural catchment using a winter storm
- if $0.15 \le URBEXT_{2000} < 0.3$
    - the catchment should by default be treated as a rural catchment with a winter storm
    - the urbanised results used with caution or as a conservative estimate. If the urbanised results are used an IF of 0.3 should be retained but a Tp factor of 1 should be used as there is no evidence for enhanced routing of urban runoff
    - if urbanised results are used a winter storm should be used for all catchments with BFIHOST < 0.65 or SAAR ≥ 800mm - for catchments with BFIHOST ≥ 0.65 and SAAR < 800 mm a summer storm may be used

For estimating greenfield runoff rates and storage design it is recommended that a winter storm is used in all applications.

9.4 Estimating time to peak in small catchments

The time to peak parameter Tp is determined within ReFH2 by one of two equations: an equation for catchments larger than 0.5 km^2 and a plot-scale equation for the smallest catchments below the scale of the drainage networks defined in the FEH Web Service. The catchment-scale estimates of Tp are a function of PROPWET, DPLBAR and DPSBAR, while the plot-scale estimates are a function of PROPWET, AREA and SAAR and therefore independent of drainage network properties (Wallingford HydroSolutions 2016a).

The original calibration of the ReFH model was carried out using rainfall and streamflow data with an hourly time step, and therefore there is a theoretical lower limit to the calibration of Tp of one hour. Based on this theoretical consideration and a relatively small sample of plot-scale data sets (see Section 10), a lower limit to the estimates of Tp of one hour is applied within the ReFH2 software. This section explores whether this lower limit is appropriate within a small catchment and plot-scale context where the catchment descriptor and plot-scale equations for Tp may be calculated to be smaller than this one-hour threshold. This research is presented in full in project report R6.

9.4.1 Catchment scale assessment of sensitivity of peak flow estimation to Tp lower bounds

The catchment-scale context was investigated using results for 143 essentially rural catchments, with AREA < 40.9 km^2 and FARL > 0.9 that were suitable for QMED estimation, using both the catchment equation and plot-scale equation to calculate Tp.

For each of the 143 catchments, the catchment equation Tp and plot-scale Tp were calculated. Then QMED (median annual maximum flood) and Q100 (100-year return period) were calculated using either the unrestricted value for Tp or the limited value of Tp

(Tp set to 1 if calculated Tp < 1). To analyse the results, QMED estimates were compared to gauged values, and Q100 to existing pooled estimates.

The 14 catchments where the catchment equation estimate of Tp was less than one hour (without limiting) tended to be the wetter, steeper and somewhat smaller catchments within the data set. This was also the case for the plot-scale equation (catchments with high SAAR and PROPWET are generally steep as well as wet), which gave Tp less than one hour (without limiting) in 15 catchments.

The bias and factorial standard error (fse) of QMED estimates obtained for these are presented for both the constrained and unconstrained cases in Table 48 for the catchment equation case and in Table 49 for the plot-scale case. In both tables the current QMED estimated using the statistical catchment descriptor equation is also presented.

These results confirm that bias and the fse are lower when Tp is constrained to a minimum of one hour and performance is comparable to the FEH statistical QMED equation (QMED_{CDS}).

Table 48 - Measures of fit obtained using catchment equation with (Tp1) and without (Tp) limits on Tp

Measure	QMED Tp1	QMED Tp	Q100 Tp1	Q100 Tp	QMED_{CDS}
Bias	1.20	1.48	1.26	1.56	1.28
fse	1.52	1.75	1.57	1.83	1.45

Table 49 - Measures of fit obtained using plot-scale equation with (Tp1) and without (Tp) limits on Tp

Measure	QMED Tp1	QMED Tp	Q100 Tp1	Q100 Tp	QMED_{CDS}
Bias	1.19	1.51	1.25	1.58	1.17
fse	1.50	1.80	1.54	1.72	1.37

These results indicate that a lower Tp limit of 1 should be retained and that within small catchments it is marginal as to whether the catchment Tp or plot-scale Tp equation should be used.

It is recommended that the catchment Tp equation should be used where possible for typical small (< 25 km^2) catchments. For catchments close to 0.5 km^2, the catchment equation should be used, unless unusually high or low values of DPLBAR or DPSBAR give a clear justification to using the plot-scale equation.

9.4.2 Plot-scale assessment of sensitivity of greenfield peak runoff rates to lower bounds on Tp

Within greenfield runoff rate calculations, it is currently accepted practice to estimate runoff rates for a nominal area of 0.5 km^2, and then to linearly scale the results to plot scale, though this dates to the IH124 methods for small catchments (Marshall and Bayliss 1994). To test the sensitivity of plot-scale calculation to a lower limit to Tp, a synthetic data set was generated by setting area for each of the small catchments within the data set used in the previous section to 0.5 km^2. Tp was calculated using the plot-scale equation. QMED and Q100 were estimated, either taking the calculated value of Tp, or the limited value (Tp set to 1 if the calculated value is < 1). Of the 143 catchments, 48% had Tp < 1 when the area was set to 0.5 km^2. These results were compared with the results obtained when the unconstrained values of Tp were used.

Figure 28 compares the constrained and unconstrained estimates and Figure 29 compares both sets of estimates with the QMED estimates obtained from the statistical catchment descriptor QMED equation. These figures demonstrate that using a Tp limited to a minimum of one hour gives a lower peak flow (in terms of QMED estimates), which provides a more conservative peak flow estimate (that is, the allowable rate of drainage from the site will be lower). Additionally, peak flows with the limited value of Tp are still broadly in agreement with the catchment descriptor derived value for QMED.

Note that this analysis uses synthesised data and should not be taken as analysis of true values of Tp at the plot scale. This is explored for a very limited set of plot-scale data in Section 10.

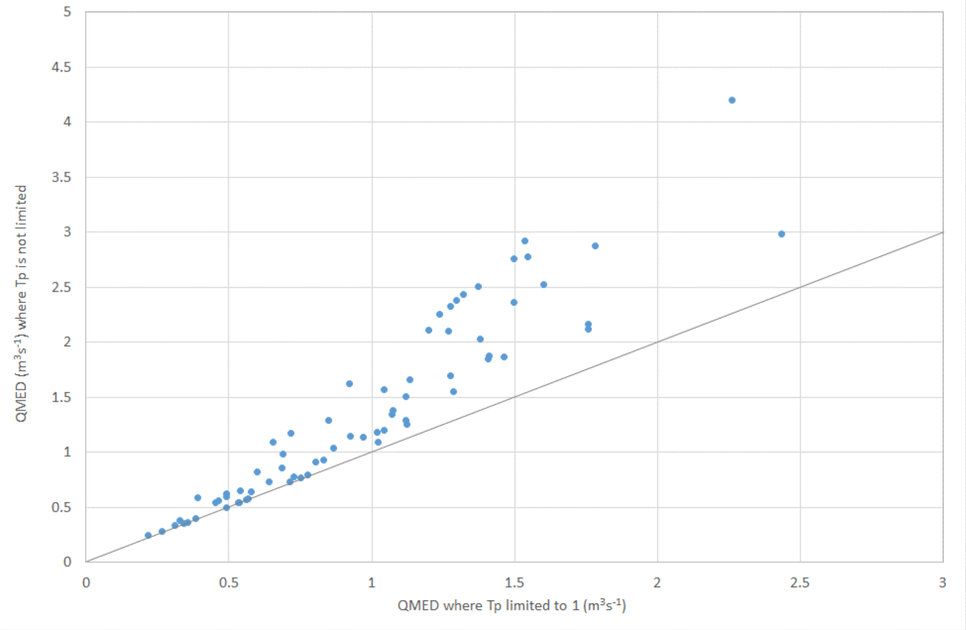

Figure 28 - Estimates of QMED comparing where Tp is, and is not, limited to 1

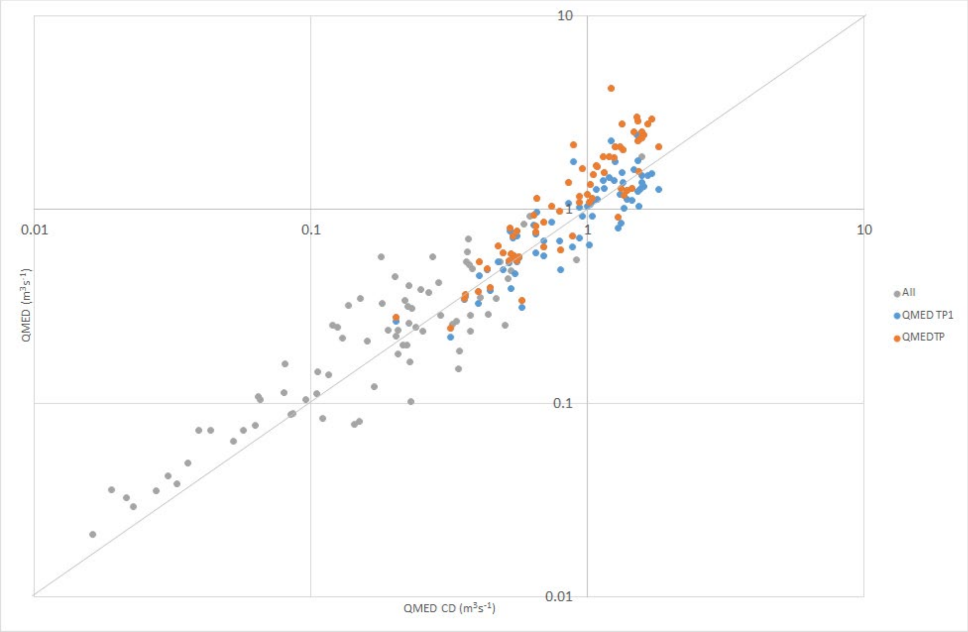

Figure 29 - QMED as estimated using ReFH and the FEH statistical (2008) equation for an area of 50 hectares

9.5 Estimating design hydrographs in small catchments

The form of an estimated design event hydrograph, in addition to the estimate of peak flow, is important in both the hydraulic modelling of fluvial events and in drainage design.

The development of the ReFH design packages was based on relationships between the parameter values obtained through calibration of the ReFH model with a representative set of catchments and the characteristics of those catchments. As the replication of hydrograph shape forms part of model calibration, then this will feed through into the design package equations for model parameters. However, in the design application the duration and storm profiles (in part determined by the estimate of Tp) will also strongly influence shape. A distinction between event volume and hydrograph shape is made; event volume within the ReFH model is determined by rainfall depth, initial conditions, the value of C_{max} and the value of BR. This study has been restricted to considering hydrograph shapes.

This section presents a comparison of the ReFH2-FEH13 hydrograph shapes with those derived empirically through an analysis of observed events for a relatively small set of catchments. The purpose of this comparison is a reasonableness test: are the hydrograph shapes similar within the context of the uncertainties in both methods? Where the shapes are different, reasons have been sought for those differences.

The empirical median hydrograph (EMH) (Archer 2000) was used for the empirical evaluation of hydrograph shape for individual catchments. This method statistically determines an index hydrograph by taking median hydrograph widths at a set of percentages of peak flow p (DOE_p) from 15-minute data observed during the largest flood events. This is computed individually for the rising and receding limbs producing a non-dimensional hydrograph shape. Similar methods have been applied in the Flood Studies Update (O'Connor and others, 2014).

The ReFH2 design package (Wallingford HydroSolutions 2016a) uses a baseflow model, loss model and the FEH13 rainfall model to produce hydrographs based on the convolution of instantaneous 'kinked' unit hydrographs. These models are described by four key parameters, maximum soil moisture capacity, unit hydrograph time to peak, Tp, baseflow lag and baseflow recharge, all available from catchment descriptor data.

Twenty catchments were ultimately chosen over the small catchments data set to cover a wide range of urbanisation, baseflow index and catchment response times. For the EMH, the top 20 peak flows recorded were used to generate the hydrograph shapes. These peak flows were detected automatically by HWA software (National University of Ireland, Galway), and manually validated. For the ReFH2 hydrograph, catchment descriptors and FEH13 rainfall model parameters were obtained from the FEH Web Service (Centre for Ecology & Hydrology, accessed Feb 2017).

To visualise uncertainty in the EMH, the sample standard deviation and L-CV were computed. Typically, one might expect for normally distributed data about a median that 65% of the data would lie within one standard deviation of the median. The value of L-CV ($0 < \tau < 1$) quantifies the variability of the peak flows; if L-CV > 0.35. This suggests high variability in the data, and that maybe a single design storm hydrograph completely describes the flood regime at such a site. Indeed, the catchments with highest standard deviation or L-CV showed the most discrepancy between the two hydrograph methods. All but six showed reasonable spread compared to the standard deviation and L-CV.

Figures 30, 31 and 32 and Table 50 show hydrographs and L-CV values for three example catchments. The main reasons for differences between the two methods were typically geological, which lead to much slower (Higher Alham) or flashier (Hitchin) responses than predicted by ReFH2. Sprint Mill shows an example of good agreement.

Table 50 - L-CV values for example catchments

Station No.	Catchment	L-CV of 50% width (Rising)	L-CV of 50% width (Receding)
52026	Higher Alham	0.380	0.371
33065	Hitchin	0.508	0.361
73009	Sprint Mill	0.187	0.200

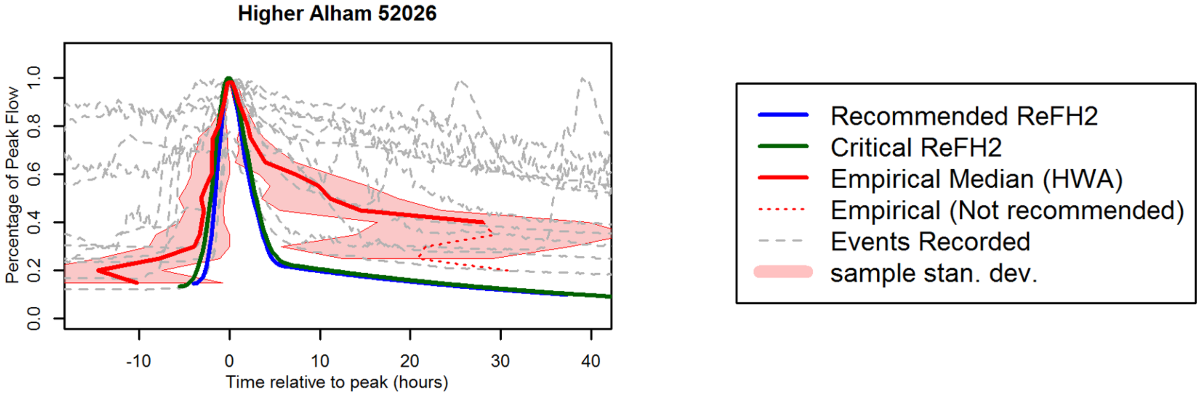

Figure 30 – Hydrograph showing discrepancies between methods for Higher Alham

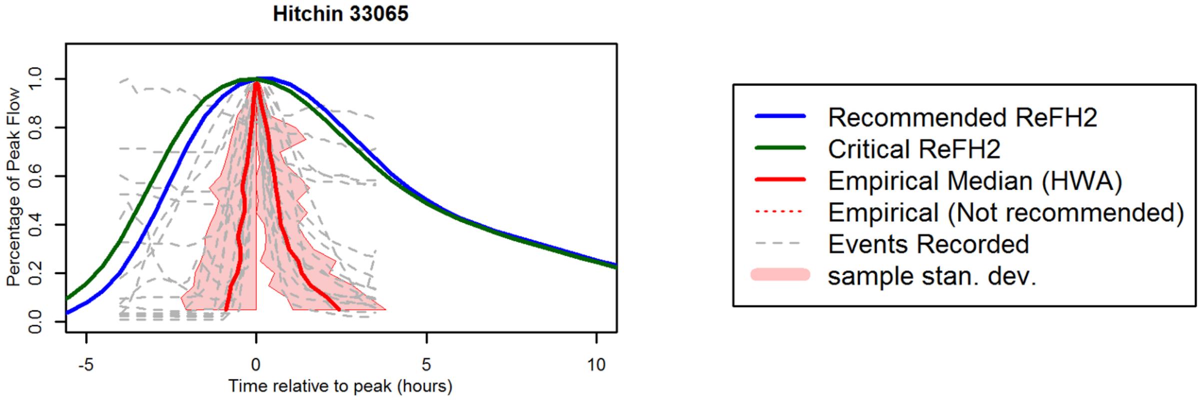

Figure 31 – Hydrograph showing discrepancies between methods for Hitchin

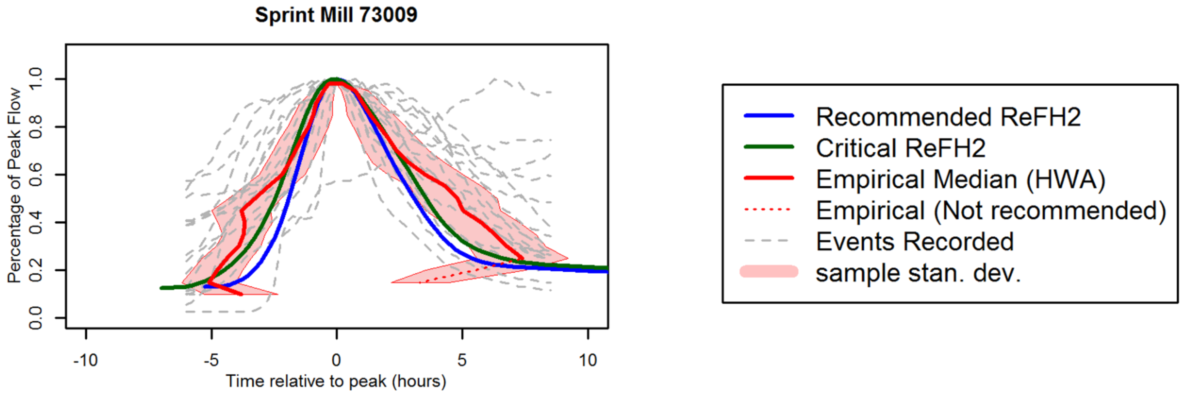

Figure 32 – Hydrograph showing discrepancies between methods for Sprint Mill

It was observed that the empirical hydrographs were particularly volatile at low percentage points, due to a lack of data for these low flows. In these cases, the Flood Studies update suggested rolling means, or omission of non-monotonic sections as seen in the Higher Alham hydrograph. This may be improved by better peak detection, larger numbers of events chosen, and wider observation windows to ensure the whole flood event is recorded.

Over the 20 catchments, more than 14 showed good agreement between the ReFH2 model and the EMH. Out of the remaining six, two were highly urbanised catchments, three suffered from short windows of observation or a short period of record, and Heighington was a poor fit due to being predominantly baseflow rather than runoff. This led to problems in the definition of the hydrograph shape. However, it is important to state it remains difficult to characterise typical normalised hydrograph shapes in highly urbanised and/or groundwater-dominated small catchments using any methods; this includes both rainfall runoff methods and empirical hydrograph methods. Caution should be exercised in these catchments when the shape of the hydrograph, over and above the estimation of event volume is important.

9.6 Recommendations

9.6.1 Seasonality

The choice of summer or winter storm in ReFH2 depends on the catchment descriptors $URBEXT_{2000}$ and BFIHOST:

- summer storms should be used if $URBEXT_{2000} \geq 0.3$ or
if $URBEXT_{2000} \geq 0.15$ *and* BFIHOST ≥ 0.65
- winter storms should be used otherwise
- these rules are scale independent - therefore, they apply to all catchments, not just small catchments

The current summer storm profile used in ReFH2 is more peaked than is realistic. Further research on summer storm profiles is recommended, across the full range of catchment scales.

Until this research is done, a new ‘summer C_{ini}’ has been produced for use with summer storms. This should always be used when summer storm profiles are selected.

A winter storm should always be used when using ReFH2 to estimate runoff rates and volumes for drainage design.

9.6.2 Urbanisation parameter selection

If $URBEXT_{2000} \geq 0.3$, a Tp factor of 0.5 and a default IF of 0.3 should be used. The IF can be revised, based on detailed mapping.

The evidence for applying the urbanisation model below $URBEXT_{2000}$ values of 0.3 is not strong. However, this lack of evidence for the impact of urbanisation below a threshold of

0.3 is also apparent for applications of the statistical method although it is still common practice to adjust for urbanisation.

Accepting this precedent, if $URBEXT_{2000} < 0.3$, a Tp factor of 1 and a default IF of 0.3 can be used, recognising this may provide a precautionary estimate of peak flow and direct runoff volume. This suggestion is independent of the value of BFIHOST or of the chosen storm seasonality. The IF can be revised based on detailed mapping.

9.6.3 Time-to-peak (Tp)

The current lower limit on Tp (one hour) should be retained, that is, if the equation for Tp estimates a value below one hour, this value should be rounded up.

The catchment-scale Tp equation, with PROPWET, DPLBAR and DPSBAR, should be used rather than the plot-scale Tp equation whenever it is possible to do so, except in catchments where the value of either DPLBAR or DPSBAR is an outlier relative to UK catchments as a whole, for example, where the catchment is an elongated valley with little contributing area above the head of the valley.

10. Estimating plot-scale runoff

This section evaluates the suitability of existing FEH methods for plot-scale applications, starting from the hypothesis that dominant hydrological processes at hillslope or plot scale may be very different from those at larger scale, even if the larger scale is still only a few square kilometres. Analysis of three small plots (0.44 to 1.03 ha) provides some limited evidence that methods based on the plot scale (that is, where catchment descriptors have been adjusted or QMED estimated directly from plot peaks-over-threshold data) may produce higher estimates of QMED than methods based on scaling results from larger catchments.

Further details are presented in **project report R7**.

10.1 Introduction

The report from phase 1 of this project included a discussion of the relevance of analysing runoff data from plots, that is, runoff that has not yet entered a watercourse. There is a large demand for estimates of greenfield run-off, and yet these estimates are usually made using methods that were developed from stream flow measurements at the small catchment scale, rather than runoff measurements at the plot scale. Most gauged small catchments are larger than 1 km^2, whereas many development sites are under 1 hectare, that is, at least 100 times smaller.

The phase 1 report also discussed the processes involved in flood generation and how these differ between large and small catchments, and between areas with a stream network bounded by a watershed and those with no natural drainage system. It was pointed out that even if an area does not appear to yield local surface runoff, it does not mean that it is not contributing to storm flow in the stream network further downstream. A notable conclusion was that “with the true source of observed streamflow undefined, and with the changing balance between in-field and in-channel processes, the extrapolation of flood estimation across catchment scales is uncertain.”

Two short analyses were carried out within the current project:

1. an investigation of plot-scale runoff data
2. an evaluation of an early version of ReFH2-FEH99 for plot-scale estimation of QMED

It is important to note that since phase 1 was published, and parts of phase 2 were completed, considerable modifications have been made to the FEH design event (ReFH) method and the ReFH1 method has been superseded by ReFH2 (Wallingford HydroSolutions 2016). ReFH2 was developed by Wallingford HydroSolutions outside this project.

10.2 Analysis of plot-scale runoff

Data from two sources were made available to the project: the Pontbren experimental catchment (a single plot) in mid Wales and the North Wyke facility in Devon (two plots).

The North Wyke site, located on Rowden Moor near the River Taw in Devon, includes 12 lysimeter plots, each around 1 ha, along with two slightly smaller plots (Rodda and Hawkins 2012). Runoff data were provided by Rothamsted Research for two plots, one drained (Plot 4) and one undrained (Plot 8).

The Pontbren plot is in mid Wales in the headwaters of the Severn catchment, an upland area dominated by sheep farming. Runoff was measured at a small hillslope which drains via a field drain with a contributing area of 0.36 ha and via overland flow from an area of 0.44 ha. Both drain flow and overland flow were monitored, the latter by means of a gutter inserted into the ground. Stream flow was measured at various locations across the catchment. Data from Pontbren were provided by Imperial College.

An analysis of the original ReFH design hydrograph method (ReFH1) demonstrated that estimates of QMED scaled (linearly by area) from downstream catchments tend to be lower than those derived from the ReFH1 model calibrated to observed plot-scale events, or from adjusting catchment descriptors to the plot scale. Similar results were found for the FEH QMED equation. The finding has different implications depending on whether the purpose of the exercise is to estimate the runoff at the outlet of the plot or the contribution of the plot to downstream flood risk. In either case, it is important to consider the hydrological characteristics of both plot and downstream catchment.

Since the original analysis of the performance of ReFH1 using the plot-scale data, the ReFH2 method has been released. ReFH2 addresses some of the concerns referred to above by providing an option for estimating parameters using catchment descriptors that do not depend on the presence of a stream network. An evaluation of the first version of ReFH2 using the FEH99 rainfall demonstrates that the modelling framework is broadly appropriate for simulating runoff generation in the relatively impermeable plots for which data were available.

11. Using local data in small catchment flood estimation

During the project, a study of the relationships between catchment vegetation, land management and flood runoff was carried out to explore their potential for improving small catchment flood estimation. A review of the literature on hydrologically monitored catchments revealed that it is difficult to generalise about the effects of vegetation and land management at the catchment scale. Moreover, there are few tools available to allow practitioners to quantify the likely effects of different types of vegetation and land use on the flood frequency curve. Hydrologists are therefore recommended to seek local data where possible and use their judgement when faced with unusual catchments.

Further details are presented in **project report R8** and 'Making better use of local data in flood frequency estimation' (**Environment Agency, 2017)**.

11.1 Introduction

A short review of existing research on the relationship between catchment vegetation, land management and flood runoff was carried out in the early stages of the project. The aim of the review was to assess the potential of using information about vegetation and land use to improve design flood estimation in small catchments. Details are available in project report R8. Related research within 'Making better use of local data in flood frequency estimation' (Environment Agency, 2017) considered the benefits of using local data, such as data from temporary river gauges, river channel dimensions or information about historical floods, to reduce uncertainty in flood frequency estimates.

11.2 Results

Agricultural land use and forestry were considered separately, and the results indicate that since most studies are site specific, making generalised extrapolations to other sites or catchments with their own particular set of conditions is extremely problematic. Few tools were identified that allow practitioners to assess the quantitative effects of catchment vegetation and land management on flood frequency.

11.3 Discussion and recommendations

Of all catchment types, the smallest are the most likely to benefit from considering the influence of features such as land cover and vegetation. There has been a wealth of research investigating the complex effects of land use management on flooding, but there is still a fundamental need to continue with long-term, multi-scale catchment monitoring studies into this topic, together with associated modelling initiatives. Current initiatives are focused on the potential benefits of natural flood management measures to reduce and delay flood flows.

Several developments in recent years could potentially be applied to improve the estimation of design flows in small catchments. For example, the spreadsheet-based catchment flood management plan (CFMP) tool (Environment Agency 2010) was designed to account for the influences of changes in land use and land management on design flows at a CFMP policy unit scale. However, it can also be applied to estimating present-day design flows, accounting for crop types and field conditions. Some work would be needed to apply the tool at a local scale.

The semi-physical distributed modelling approach, as used for some investigations into natural flood management, may also potentially be used to incorporate information on land management when estimating design flows. However, it is a complex technique which has not yet been implemented and may be too difficult to apply in most studies that require flood estimation in small catchments.

An Environment Agency research project, ‘Making better use of local and historical data and estimating uncertainty in FEH design flood estimation’, reviewed and developed techniques for incorporating local data in flood estimation. It uncovered examples of site-specific hydrological reasoning being applied to allow for the influence of unusual catchment properties (Environment Agency 2017).

Merz and Blöschl (2008) provide some examples of how field visits or examination of topographic maps can yield clues about the flood frequency behaviour of catchments, such as the degree of incision of valleys, the presence of indicator plants, or the characteristics of the river channel. The authors state that “It would not be possible to predict the differences in catchment response between the two catchments on the basis of the quantitative catchment attributes and formal methods alone. In contrast, soft information obtained through a visual examination of the catchments during site visits may help tremendously. Clearly, site visits are instrumental in a hydrological assessment.”

One recommendation of the ‘Making better use of local data in flood frequency estimation’ project was that a change in culture is needed to get hydrologists away from their computer models and into the field more often. Site visits are not always budgeted for in some UK hydrology practice. This is understandable when studies of large geographical areas are commissioned. However, small catchments do not take as long to explore. There is much that can be inferred about the characteristics of a small catchment by closely inspecting detailed maps and aerial photographs. Both are valuable for identifying unusual features, including vegetation types and land management practices that might be missed in a digital summary of catchment properties. However, some types of information can only be gained by site inspection and survey.

Another suggestion would be to test whether descriptors of vegetation or land management can be used to explain any of the residuals from the current FEH methods when applied to the small catchment monitoring database.

Even without any models or software tools that allow practitioners to account for information on land use when estimating design flows, hydrologists should be capable of applying their judgement when faced with unusual catchments. This requires both a grounding in catchment science and a sound understanding of the assumptions and principles of modelling techniques. This does raise educational and training implications that could potentially increase costs – or trend towards an overly-prescriptive use of analytical tools.

12. Investigation of high intensity, short-duration rainfall

In the early stages of the project, a depth-duration-frequency (DDF) analysis of short-duration rainfall data for 19 rain gauges in England and Wales was carried out. A modified version of the generalised extreme value distribution was used to model the annual and seasonal maxima for a range of durations from one to 120 minutes at each site, giving a good fit to the observed data and performing well for shorter return periods (2, 5 and 10 years) for which reliable estimates of rainfall frequency can be obtained from observations. Comparisons with the results from standard national DDF models showed that even though the existing methods used little or no sub-hourly data in their calibration, they gave fairly reliable estimates of rainfall, with low bias and moderate scatter when compared to gauged estimates of the 2-, 5- and 10-year rainfalls for different durations.

Further details are presented in **project report R9** and **Prosdocimi and others (2017)**.

12.1 Introduction

Small catchments and plots often respond rapidly to storm events, making them potentially vulnerable to short, intense bursts of rainfall. Therefore, short-duration rainfall estimates are needed for flood risk management as well as for development control and the design of sustainable urban drainage systems (SuDS). The aim of this part of the project was to investigate the depth-duration-frequency (DDF) characteristics of short-duration rainfall data by creating single-site DDF models based on a unified GEV (generalised extreme value) distribution. This model cannot and is not intended to be generalised to the whole UK, due to the limited data available for its development (497 years at 19 stations) and the difficulty of capturing behaviour across such a large range of durations with a simple structure and few parameters; the limited availability of data required a structure with few parameters. However, the single-site unified GEV was successfully used as a tool to assess the ability of current national models (FEH and FSR) applied at sub-hourly durations.

12.2 Data

Nineteen sites with relatively long periods (15 to 46 years ending in winter 2013 to 2014) of high-resolution rainfall records were initially selected to provide good coverage of England and Wales. Data of the highest temporal resolution came from nine tipping bucket rain gauges where the rainfall data were recorded as time-of-tip, representing the instant when a bucket of fixed volume was filled and subsequently reset. These were reprocessed to represent depths of rainfall over one-minute intervals. However, 10 of the rainfall records available to the study were only available as 15-minute rainfall accumulations. Therefore, the final data set consisted of nine gauges with basic data at one-minute intervals and 10 gauges with data at 15-minute intervals. Fifteen of these gauges had more than 20 years of data and the longest two records were both 46 years. All gauges are mapped on Figure 33.

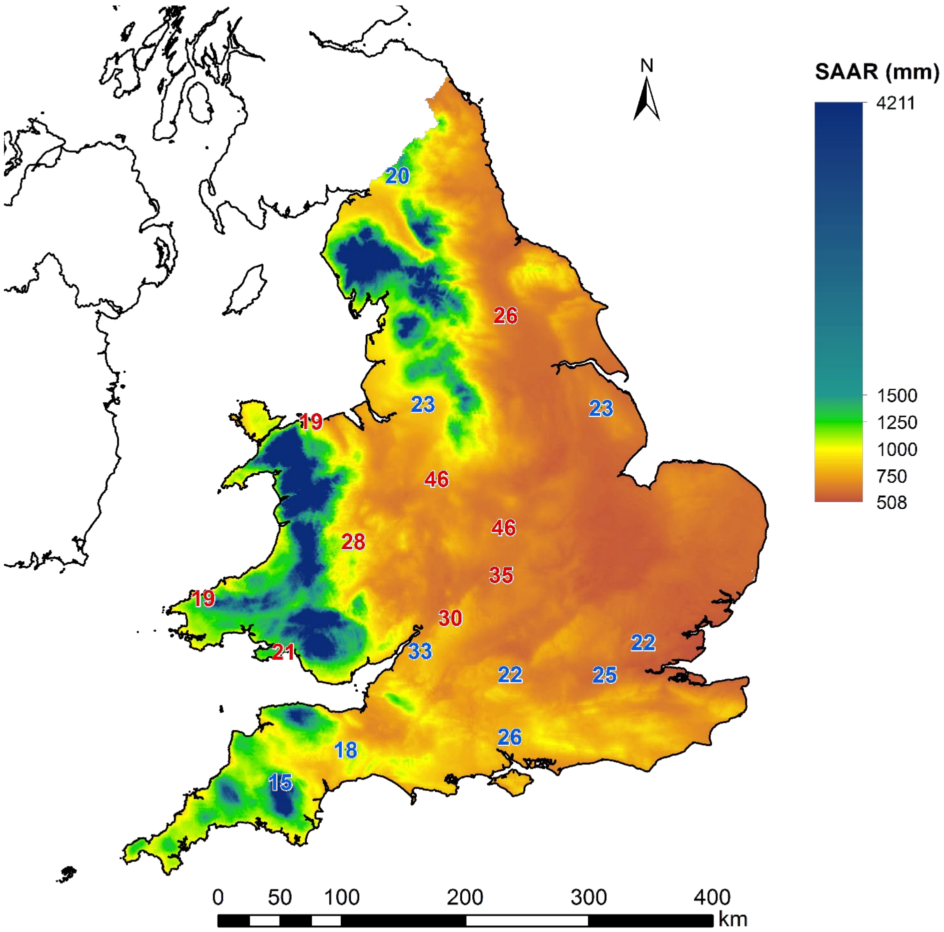

Figure 33 - Location of the 19 stations in England and Wales included in the study.

The map in Figure 33 shows the 19 stations included in the study. The record length of the annual maxima series is indicated in the location of each station: red numbers indicate time-of-tip stations, blue numbers indicate 15-minute stations. The SAAR (from 508 to 4211 mm) is shown as a heat map ranging from orange to blue.

Annual maxima of 15, 30, 45, 60, 90 and 120 minutes' duration were extracted for each gauge-year in which at least 11 months were at least 75% complete. Annual maxima of one, 2, 5 and 10 minutes' duration were also extracted for the nine reprocessed one-minute records, according to the same completeness criteria. Maxima extracted from the 15-minute records were multiplied by correction factors (Table 51), to reflect the fact that 15-minute accumulations from a 1-minute series are always larger than 15-minute accumulations from 15-minute series.

Table 51 - Correction factors applied to maxima extracted from 15-minute series

Duration (minutes)	15	30	45	60	90	120
Correction factor	1.15	1.05	1.03	1.02	1.02	1.01

12.3 DDF analysis

The aim in building a DDF model was to find a single model structure that could be fitted separately at each station by varying its parameter values. An initial exploration of the data was carried out to inform the building of the statistical model, including the relationship between event duration and L-moments of annual maxima. The generalised extreme value (GEV) distribution was used for its practical utility and theoretical justification (Equation 30).

Equation 30 - The quantile function for the GEV distribution

$$x(F) = \begin{cases} \xi + \dfrac{\alpha}{\kappa}\left[1 - (-\ln F)^{\kappa}\right] & \text{if } \kappa \neq 0 \\ \xi - \alpha \ln(-\ln F) & \text{if } \kappa = 0 \end{cases}$$

In this equation, ξ, α and κ are the location, scale and shape parameters respectively. For κ ≠ 0, α was reformulated in terms of ξ and the distribution lower bound, ℓ, while ξ was reformulated in terms of duration*, D,* in order to estimate rainfall frequency curves for different durations that never cross each other and only increase with return period:

- $\alpha(D) = \left(l - \xi(D)\right)\kappa$
- $\xi(D) = a + bD + c(1 - \exp\{-gD\})$
- $b + cg\exp\{-gD\} > 0$

Where a, b, c and g are station-specific constants that do not vary with duration or return period, and D is a standardised duration, equal to the duration of the AMAX (one to 120 minutes) divided by 480. Therefore, this so-called unified GEV distribution builds on standard extreme value theory and ensures consistency between estimated frequency curves by fixing some basic relationships between the model parameters and assuming a common lower bound for all event durations. The proposed unified GEV requires the estimation of six parameters, and this is a relatively simple model for such a complex problem.

The unified GEV model was fitted to the data series at all stations. In each case, the fitting of the frequency curves was a compromise between the goodness-of-fit at each duration and the consistency of curves across durations.

12.4 Comparison with existing national models

A comparison between the rainfall frequency curves estimated in the present study and those obtained from previously developed DDF models (FSR, FEH99 and FEH13) was carried out in order to assess the suitability of these models for durations shorter than one hour. However, it should be noted that the FEH13 model had not yet been fully generalised by this point in time. Comparisons were presented for a range of durations (one to 120 minutes) and return periods (1.2 to 50 years).

No structural differences were identified between the rainfall frequency curves estimated with the unified GEV and the three previously existing DDF models, although there were some patterns (with exceptions). Due to the fixed relationship between ξ and α, frequency curves produced by the unified GEV for different durations tended to 'fan out' more than those produced by the three existing models, which show less change in curvature with return period and duration. Consequently, the existing methods tended to estimate more rainfall than the unified GEV for short return periods, and less for longer return periods, variable with duration. However, in Wales, the existing methods always estimated more rainfall than the unified GEV. This may be due to climatological or data management differences.

Given that the unified GEV is fitted to the series at each station separately, the length and quality of the data at each station have a major impact on the precision of the estimated curves. Therefore, it is not clear if the lack of consistent differences across the methods is a result of the differing record length and data quality at each individual rain gauge site. A much more extensive high quality data set would be needed to study this effectively.

12.5 Recommendations

The existing standard DDF models did not appear to give unreasonable rainfall depth estimates for very short durations when compared with the estimates developed from higher-resolution data in the present study. Considering that the standard DDF models were developed using little or no rain gauge data for durations shorter than one hour and are designed to be used for a range of event durations, it is reassuring to see that the results obtained when extrapolating to such short durations appear to be reasonable.

Unfortunately, the very limited available data prevent the creation of either a UK-wide or regional model for sub-hourly data. Therefore, this study made the following recommendations to users requiring short-duration rainfall estimates:

- the FEH13, FEH99 and FSR DDF models appear to provide reasonable estimates for frequencies of sub-hourly rainfall events down to a duration of 15 minutes, at least for the short return periods (<10 years) at which local data can be expected to provide suitable empirical evidence
- the FEH13 and FEH99 models appear to give less biased results than the FSR model and seem to be more suitable for extension to allow the estimation of frequency curves for sub-hourly rainfall durations - however, due to the

relatively small number of gauges used in the study reported here, these results should only be extrapolated to the national scale with caution

- larger uncertainties are associated with very short durations (1-minute to 15-minute durations) - the FSR, FEH99 and FEH13 models were not fully calibrated on such short durations and larger errors are to be expected in the measured data, especially in the early years of the records

Following this analysis, further work on the extrapolation of the FEH13 model to sub-hourly durations was carried out at CEH outside this project before the release of the new FEH Web Service (https://fehweb.ceh.ac.uk/). These are the preferred rainfall estimates for durations down to five minutes.

They are estimated by multiplying the FEH13 60-minute rainfall depth by the ratio of FSR x-minute depth to FSR 60-minute depth (where x is a duration of 5, 15, 30 or 45 minutes). For other durations under 60 minutes (for example, 37 minutes), the same 4-point interpolation is used as when requesting rainfall depths for non-tabulated durations elsewhere on the FEH Web Service.

13. Free greenfield plot-scale peak flow rate and volume screening data

Gridded datasets of plot-scale estimates of peak flow rates (l/s/ha) and volumes in England and Wales have been compiled using freely available data. The 1 km resolution peak flow rate estimates cover return periods of 1, 2, 30 and 100 years which are relevant to drainage design, as well as the 6-hour duration, 100-year return period event. To estimate runoff volume, a second more conservative, yet more uncertain, model was generated.

The freely available rainfall and soil data were used to fit regression models that aim to give more conservative values (low greenfield peak flow rate and runoff volume). To achieve this, a free alternative to the standard baseflow index was generated using open-source European soil data. The models seem to perform better than IH124, but not as well as those generated from ReFH2 with FEH13 rainfalls.

Conservative estimates cannot be guaranteed for any individual sites, so this tool is seen as a screening mechanism only and should also be accompanied by using the latest ReFH-FEH design package. If a more conservative estimate is required, both the free methods and the latest ReFH-FEH design package should be applied, and the more conservative value taken.

These gridded data sets are available from GOV.UK. See Appendix B for further details.

13.1 Background

The estimation of greenfield runoff rates is required for setting limiting discharge rates for new developments and therefore is used by developers, drainage engineers and those involved in assessing planning applications. In addition, surface water storage attenuation volume estimates are also needed for initial drainage design.

The standard approach assumes that the flow rate discharge constraints for storm water runoff from the site are defined by the greenfield runoff rates for the one-year (that is, 12-month return period on the peak-over-threshold (POT) scale), 30-year and 100-year return periods. In addition, greenfield runoff volume is calculated for the 100-year 6-hour event as this volume is used in the design of the drainage system.

One of the requirements of the current project was to produce a simplified free-to-use method for estimating greenfield runoff rates together with runoff rates for the 100-year, 6-hour storm event. The reasoning behind this was to provide an alternative to the widely used IH124 method which is outdated and has been superseded by the FEH methods described elsewhere in this report. Historically, the upfront costs of the occasional user accessing FEH methods and data were high. This has been partially addressed by the current access methods where the cost of access to data scales with use through the FEH Web Service.

The new free method, delivered as pre-computed data, is available to download with this report on GOV.UK (see Appendix B). Due to the limitations of what can be achieved using free-to-air data sets, the method is not guaranteed to underestimate greenfield runoff rates and volumes at all sites and is intended only to use as a screening tool to provide precautionary results at the pre-planning stage of new developments. Although every effort was made to make the results conservative, that is to underestimate greenfield runoff the estimates are generalised and not always precautionary as they are subject to considerable uncertainty. To this end, the method is intended to replace the IH124 method where this is referenced within guidance.

13.2 Data

The datasets of greenfield runoff rates and volumes have been generated using the following datasets which were made available to the project without charge:

- average annual rainfall in mm for the standard 30-year period 1941-70 ($SAAR_{4170}$) on a 1km grid:
    - this dataset was developed for the analysis that led to the Flood Studies Report (FSR) (NERC 1975) and was published in the form of paper maps in FSR Volume V
    - the 1-km gridded version of the data was generated at CEH from a digitised version of the FSR map for Great Britain and Northern Ireland during the development of the FEH methods (see FEH Vol. 5). $SAAR_{4170}$ is one of the FEH catchment descriptors available for river catchments via the FEH Web Service (https://fehweb.ceh.ac.uk)
    - the $SAAR_{4170}$ gridded dataset is owned by CEH.
- soil data from the Soil Geographical Database of Eurasia (SGDBE), part of the European Soil Database v.2.0 (provided by the European Soil Data Centre (ESDAC) http://eusoils.jrc.ec.europa.eu).
- since data from the Hydrology of Soil Types (HOST) classification (Boorman and others. 1995) are subject to licensing restrictions, permission was given for the use of SGDBE in the development of a *BFIHOST* substitute so that the resulting runoff rates and volumes could be released to users without charge - the data were supplied by ESDAC on condition that the raster and vector data files of soil types were not distributed.

An alternative soil database (CORINE) was also explored but proved to be less effective at conveying the complete range of values of base flow index (BFI).

13.3 Methodology

13.3.1 Development of BFI_{SGDBE} grid

BFIHOST (estimate of BFI from the HOST soil classification) is a key FEH catchment descriptor that provides a measure of catchment responsiveness. The HOST dataset is a 1-km grid that records the percentage of each of 29 soil classes present.

Boorman and others (1995) developed a linear regression model of the relationship between BFI and the fractional extents of HOST classes in a sample of 575 gauged catchments to provide a set of 29 BFI coefficients, one for each HOST class. This was used in the FEH analysis to derive area-weighted *BFIHOST* estimates for all catchments of at least 0.5 km^2 in the UK (Bayliss 1999).

BFIHOST is used with other variables to estimate the median annual maximum flood in the FEH statistical method and informs three out of four model parameters in the ReFH2 design hydrograph package for catchment and plot-scale applications.

In order to develop free precautionary estimates of greenfield runoff rates and volumes within this project, an alternative set of BFI estimates was constructed using the SGDBE version 4 beta (European Commission and European Soil Bureau Network 2004). This is a 1:1,000,000 scale digital soil map which splits Europe into Soil Typographical Units (STUs) described by several variables (attributes) specifying properties of the soil such as land use, soil texture and water regime.

Since these regions cannot be identified at the scale of the SGDBE, the STUs are grouped into Soil Mapping Units (SMUs) to form soil associations, which are represented as polygons. The proportion of the SMU area represented by each major STU is recorded, but not its specific location.

The alternative BFI estimates were derived by considering the intersections of each HOST class with each SMU to obtain a new set of coefficients based on SGDBE. The resulting BFI estimates are termed BFI_{SGDBE} and were estimated as average values over a 1-km^2 area centred on each 1-km grid point. It should be noted that the low resolution of the gridded soils dataset relative to the size of a typical plot introduces uncertainty into the estimation of the average values of BFI, and hence derived runoff peaks and volumes, for any particular plot.

13.3.2 Calibration and verification data

The updated version of the Revitalised Flood Hydrograph (ReFH2) design package (Wallingford HydroSolutions 2016a) was applied in plot-scale mode to notional 0.5 km^2 plots centred on the grid posts of a regular 25-km grid across England and Wales with the same origin as the British national grid. ReFH2 was applied to each plot using the FEH recommended duration ($D = T_p(1 + SAAR/1000)$) and assuming the area to be 100% rural. The ReFH2 plot-scale results were sub-divided into calibration and verification datasets by taking alternate points on the 50 km grid so that points in each set were 50 km apart both horizontally and vertically.

13.3.3 Models for peak greenfield runoff rates and volumes

The $SAAR_{4170}$ and BFI_{SGDBE} datasets described above were used as covariates to develop regression models for greenfield runoff rates estimated from ReFH2 for 12-month (corresponding to 1.58-year return period on the annual maximum scale), 2-year, 30-year and 100-year return periods. Models of peak flow rates and volumes for the 6-hour 100-year design event were also developed in the same way. In addition to $SAAR_{4170}$ and BFI_{SGDBE}, the regression models considered Northing, Easting and return period, T, as possible terms.

A similar procedure was used to develop models for the 6-hour 100-year return period peak flow rates ($Q_{100,6h}$) and the 6-hour 100-year return period runoff volumes ($Vol_{100,6h}$).

Linear regression provides the best model that explains the data by minimising error.

This, however, does not lead to conservative estimates; one would expect overestimation at half the sites in the dataset. To rectify this, coefficients were modified by selecting from a range of values for each coefficient to keep the error as small as possible (within a factor of two of the closest-fitting model) whilst introducing a negative bias (equivalent to a conservative estimate).

This resulted in three models (shown in Equations 31, 32 and 33):

Equation 31 - The peak flow rates over the four return periods (QT)

$$\ln Q_T = -2.65 + 0.206 \ln T + 1.38\left(\frac{SAAR_{4170}}{1000}\right) - 1.67 BFI_{SGDBE}$$

Equation 32 - The 6-hour 100-year peak flow rates (Q100,6h)

$$\ln Q_{100,6\text{h}} = -0.96 + 1.066\left(\frac{SAAR_{4170}}{1000}\right) - 1.885 BFI_{SGDBE}$$

Equation 33 – The 6-hour 100-year peak flow volumes (Vol100,6h)

$$\ln Vol_{100,6\text{h}} = 8.64 + (EASTING/1000000) \times \left(0.2\frac{SAAR_{4170}}{1000} - 0.4 BFI_{SGDBE}\right)$$

In these equations, Q_T is in units of m^3/s while $Vol_{100,6h}$ is in units of m^3 (Ml/1000).

The model in Equation 31 shows a reasonable fit to the ReFH2 estimates, having an adjusted R^2 value of 0.536. The fit is shown in Figure 34, with ReFH2 estimates on the x-axis and Equation 31's estimates on the y-axis. The residuals do appear to have some links to location, with similar residuals seen for different return periods for the same site.

The models in Equations 32 and 33 generally fit less well, with ln $Q_{100,6h}$ having an adjusted R^2 value of 0.528, and ln $Vol_{100,6h}$ an R^2 value of 0.444. The fits are shown in Figures 35 and 36, withReFH2 estimates on the x-axis and Equation 31's estimates on the y-axis. Note that these figures are presented on a logarithmic scale, and therefore the errors will be magnified for large events when transformed to a linear scale.

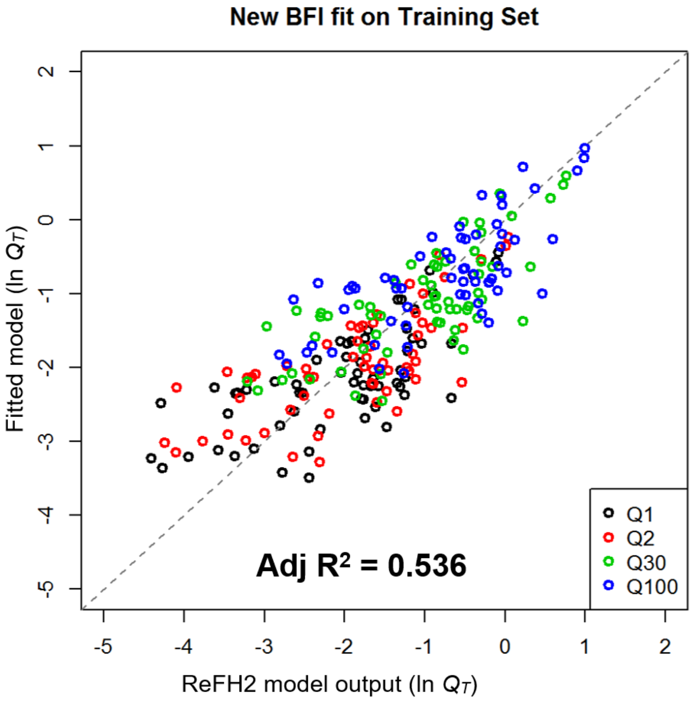

Figure 34 - Comparison of ReFH2 peak flow rates with linear model outputs for recommended durations events at four return periods (m³/s per 50 ha)

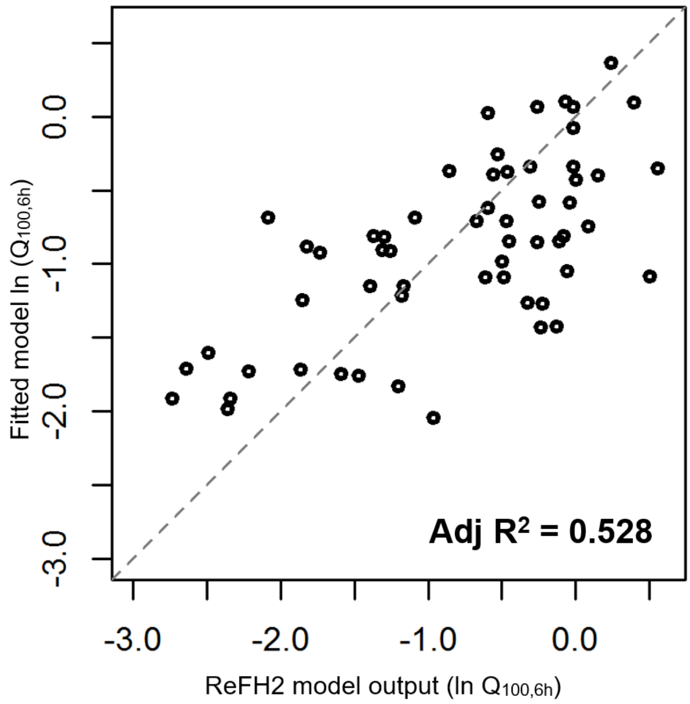

Figure 35 - Fits of 6-hour 100-year return period peak flow rate as compared to ReFH2 model

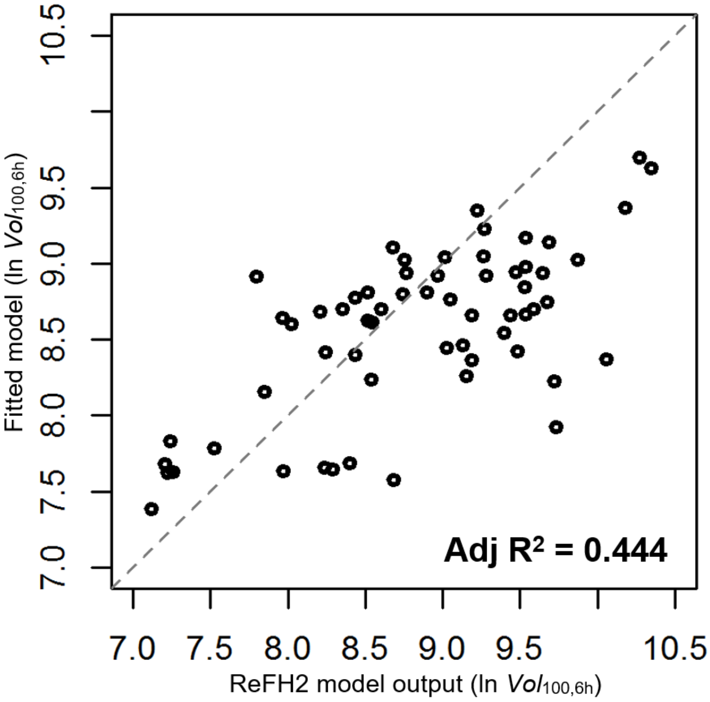

Figure 36 - Fits of 6-hour 100-year return period runoff volume as compared to ReFH2 model

To assess the performance of a model, it is standard practice to split the data into separate subsets for calibration and validation. The three models (Equations 31, 32 and 33) were developed on a calibration dataset consisting of point values on a 50-km grid of points covering England and Wales and then tested on a validation dataset consisting of points offset from the calibration dataset by 25 km in both easting and northing to check for unexpected biases or overfitting.

Goodness-of-fit statistics for ln Q_T for both the calibration and verification data sets are given in Tables 52 and 53.

The verification set shows similar goodness-of-fit to the calibration set, which suggests reasonable similarity between the two datasets, and that the model represents the data reasonably well without overfitting.

Table 52 - Goodness-of-fit statistics for ln Q_T on the calibration data set for different return periods

RP	R^2	Bias	RMSE	fse
12-month	0.540	0.92(-0.08)	0.698	2.01
2-year	0.541	0.93(-0.07)	0.688	1.99
30-year	0.536	0.70(-0.30)	0.742	2.10
100-year	0.530	0.66(-0.34)	0.765	2.15

Table 53 - Goodness-of-fit statistics for ln Q_T on the verification data set for different return periods

RP	R^2	Bias	RMSE	fse
12-month	0.490	0.80(-0.20)	0.742	2.10
2-year	0.477	0.81(-0.19)	0.739	2.10
30-year	0.471	0.61(-0.39)	0.847	2.33
100-year	0.465	0.57(-0.43)	0.881	2.41

The outputs of the free models were compared to the ReFH2 and IH124 model outputs and show a reasonable fit, outlined in Table 33 and Table 34.

The factorial standard error of the new peak flow model is 1.99 at QMED and 2.15 at 100 years, compared to 1.43 and 1.70 achieved by ReFH2 across the small catchment dataset.

The new model achieves lower fse than the IH124 model across the same dataset. However, we do note that this is *not* a strict comparison, since the ReFH2 and IH124 models were compared to known data, whereas these fitted values are compared the ReFH2 model outputs, and so this is likely to be additional error on top of the original model output errors. However, ReFH2 has been shown to be unbiased and thus the significant bias towards underestimation is a full estimate of likely bias and, although significant, it is less biased towards underestimation than IH124.

Tables 54, 55 and 56 compare the free models for the separately fitted, 6-hour, 100-year event (Equation 32 and 32) against ReFH2. Bias and fse are comparable to those for the ln Q_T model (Equation 31).

Table 54 - 2-year return period summary of fit (note that error for new models is relative to the ReFH2-FEH13 plot-scale results, not actual values)

T = 2 return period	RMSE	fse	bias
New model peak flow	0.688	1.99	0.93 (-.07)
ReFH2 peak flow	N/A	1.43	1.00
IH124 peak flow	N/A	2.05	0.73 (-.27)

Table 55 - 100-year return period summary of fit (note that error for new models is relative to the ReFH2-FEH13 plot-scale results, not actual values)

T = 100 return period	RMSE	fse	bias
New model peak flow	0.765	2.15	0.66 (-.34)
ReFH2 peak flow	N/A	1.70	0.98 (-.02)
IH124 peak flow	N/A	2.34	0.58 (-.42)

Table 56 - Summary of fit for the 6-hour 100-year event (note that error for new models is relative to ReFH2-FEH13 plot-scale results, not actual values)

T = 100, 6h duration	RMSE	fse	bias
Peak flow	0.636	1.89	0.89 (-.11)
Runoff volume	0.667	1.95	0.75 (-.25)

13.4 Outputs

Figures 37 to 42 show the greenfield runoff rate and volume estimates for England and Wales. ReFH2 results on a 50 km grid, with origin at 25 km east and 25 km north on the British national grid, were used as a validation data set. Residuals for these validation points are shown on the maps.

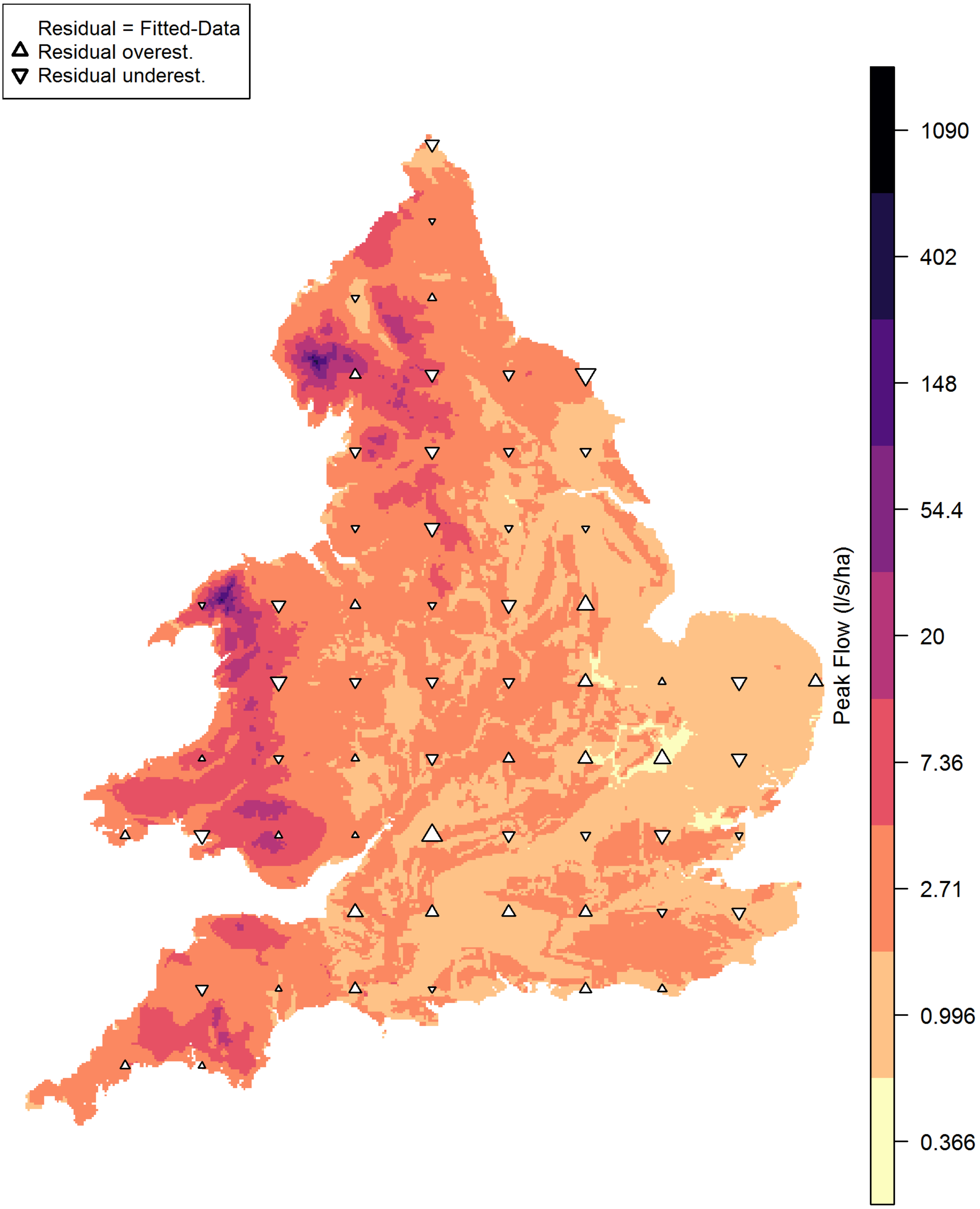

Figure 37 - Greenfield runoff rates for 12-month return period (l/s/ha)

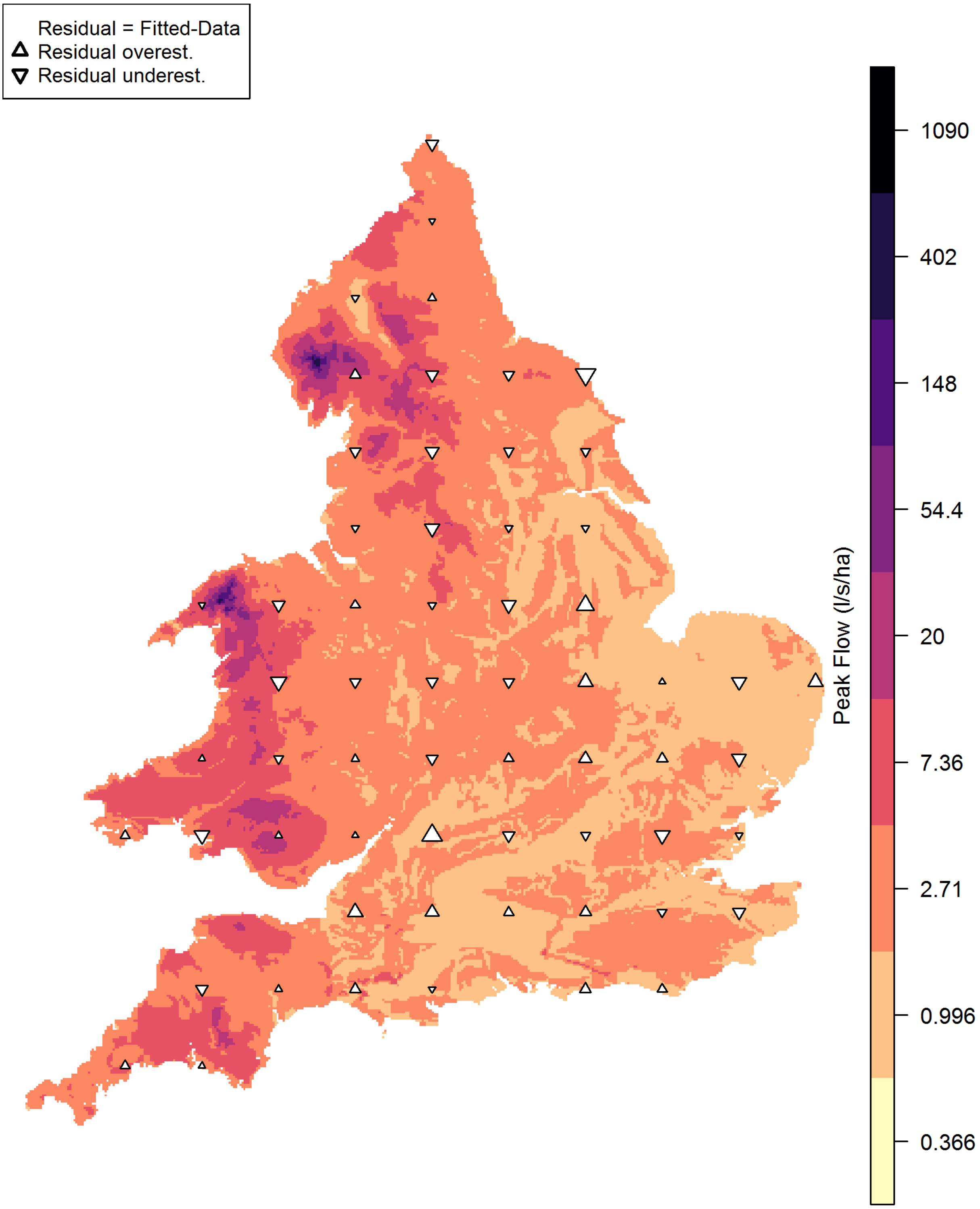

Figure 38 - Greenfield runoff rates for 2-year return period (l/s/ha)

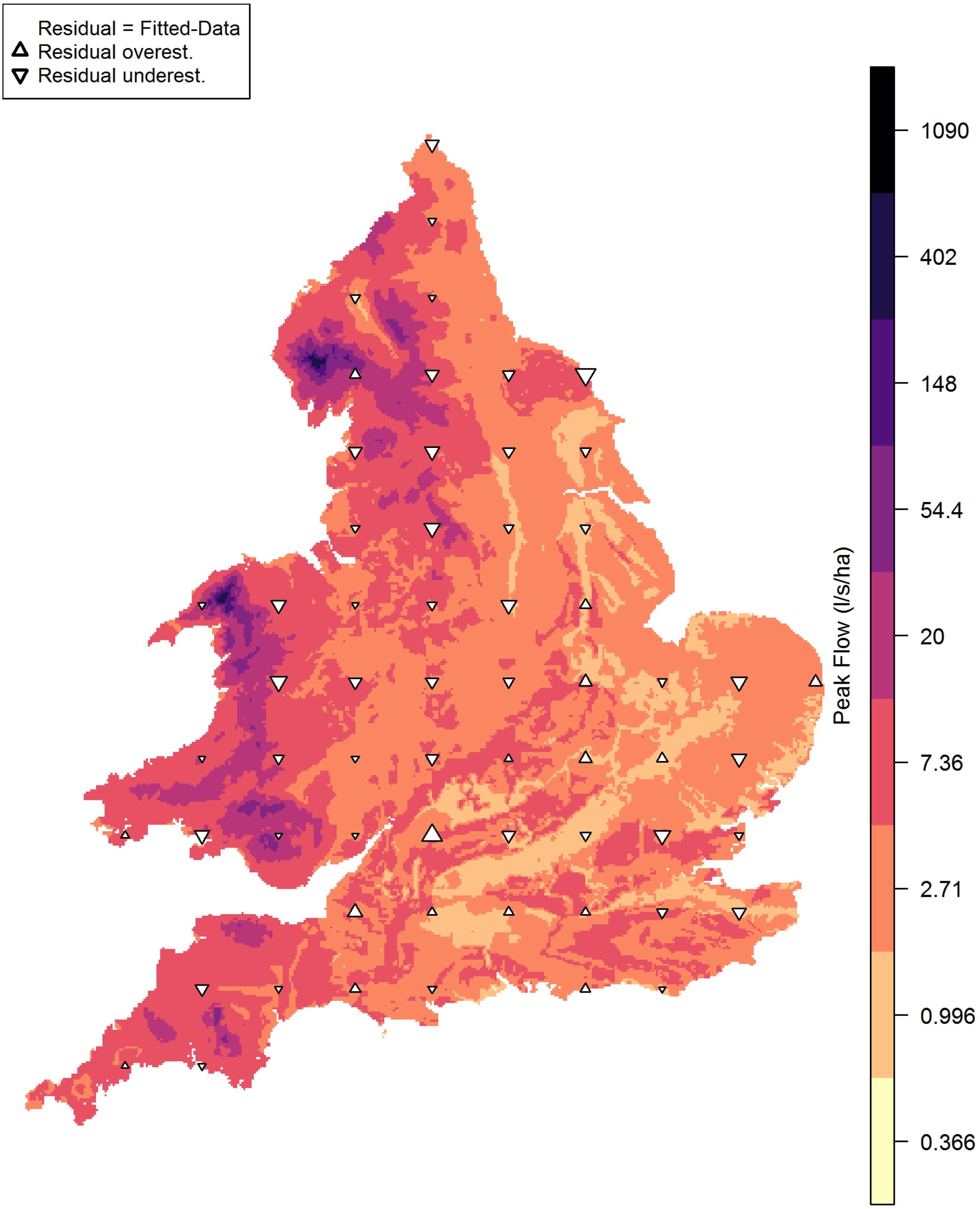

Figure 39 - Greenfield runoff rates for 30-year return period (l/s/ha)

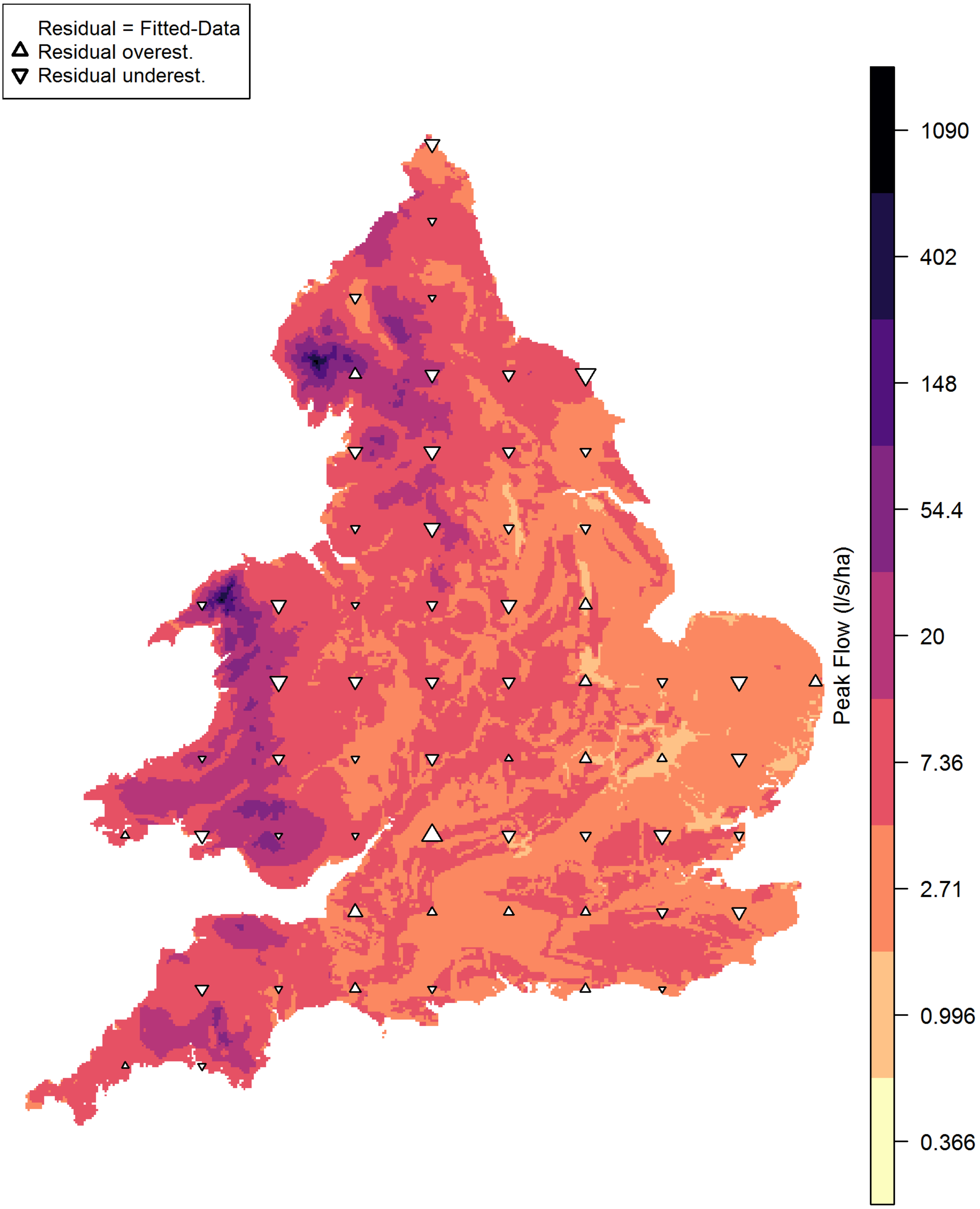

Figure 40 - Greenfield runoff rates for 100-year return period (l/s/ha)

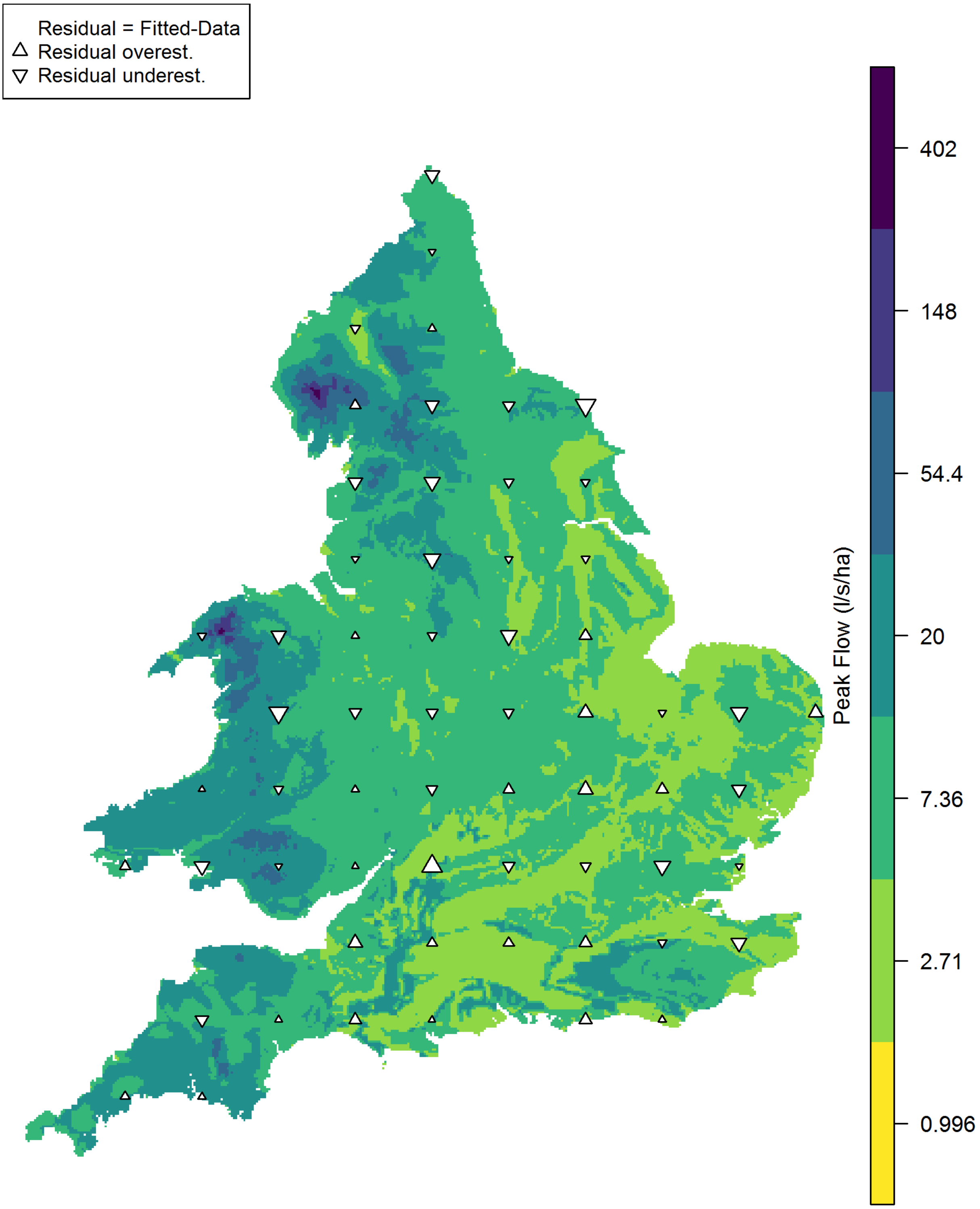

Figure 41 - Greenfield runoff rates for 6-hour duration 100-year return period (l/s/ha)

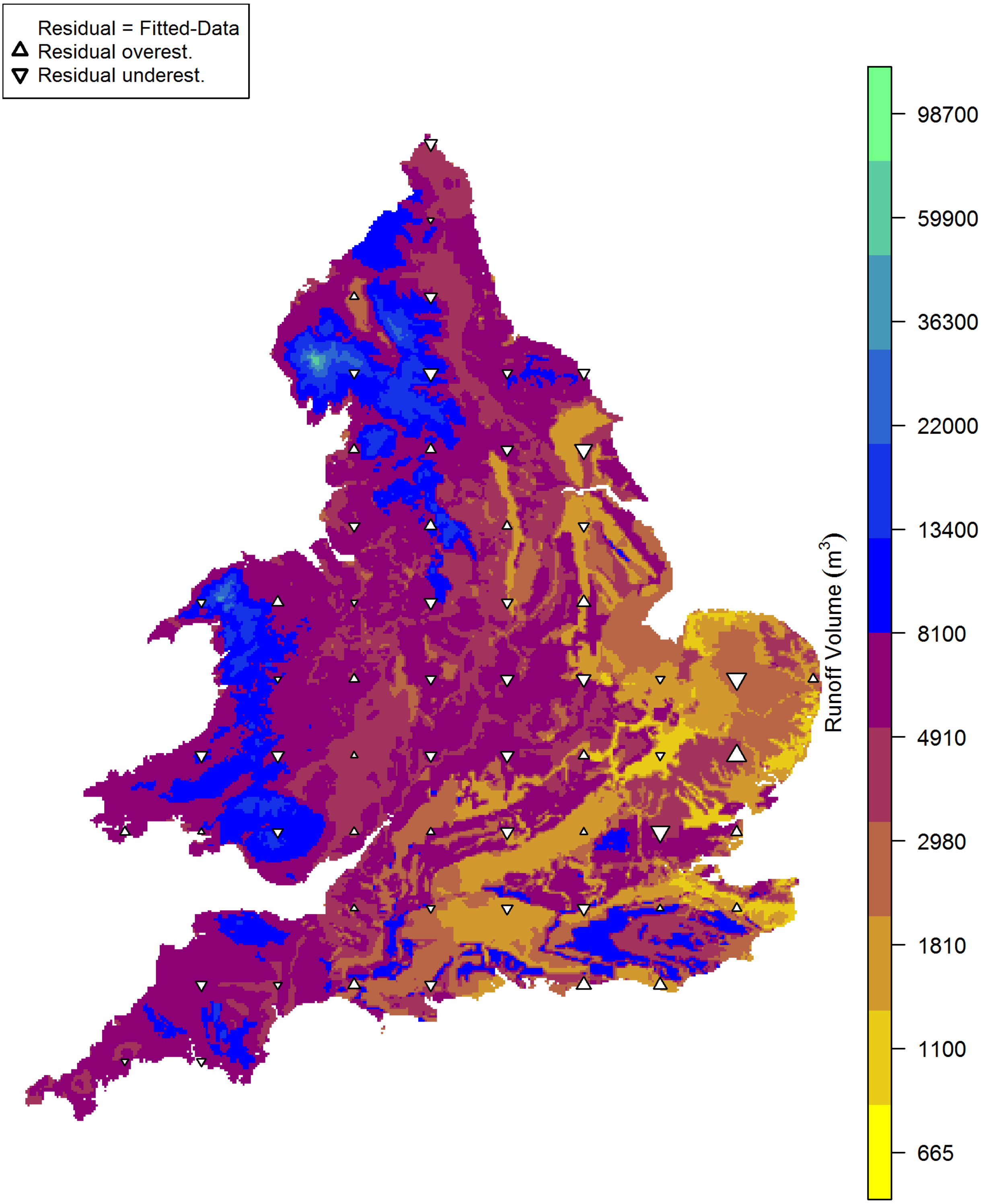

Figure 42 - Runoff volume from 6-hour duration 100-year storm event (m^3) for a 50-ha plot. For smaller plots, the volume should be scaled linearly by area

13.5 Recommendations for application

We recommend that:

- for plots much smaller than 50 hectares, at or near to one 1-km grid post, the peak flow/runoff rates given for that grid post can be used
- for plots much smaller than 50 hectares, located between 1-km grid posts, the required peak flow/runoff rate should be identified at the four grid posts surrounding the plot (coastal plots may only have three or fewer), and a simple inverse-distance weighting scheme applied to estimate the value for the plot
- for larger plots, users should make their own judgement about the spatial variation in runoff rates across the plot based on local soil information and take a weighted average of one or more estimates relevant to different sections of the plot according to their fractional coverage of the whole plot
- on average, these free models are more conservative than ReFH2, that is they are biased towards underestimating greenfield runoff rates and volumes
- although the methods are conservative on average, they cannot be considered fully conservative; runoff estimates may often be overestimated on an individual use case and could be significantly higher than the corresponding ReFH2 estimates - the free methods are significantly more uncertain than FEH methods and as such, the free methods should only be used knowing this uncertainty and should only be used with caution and in a screening context
- in all cases, using ReFH2 as a best estimate should be preferred to this method. The free methods are acceptable as a screening tool on a large scale but should not be used in isolation at single sites. The free methods, however, do perform better than the IH124 methods, and should be used rather than IH124
- if a very conservative estimate is required, then both the free methods and ReFH2 should be applied, and the more conservative value taken
- values in this dataset only apply to mainland England and Wales. Islands (such as Anglesey, Isle of Wight and the Isle of Man) are not included in this dataset - this is because some of the input data included only mainland parts of England and Wales, while some small islands on or near the coast may appear to included, they are not.
- the following should also be considered for locations near, or adjacent to the coastline:
    - in some locations, the underlying free, open-source soils data used did not have values for some coastal cells - when the model for a free BFI substitute was fitted, no BFI could be generated for these locations, and hence no values for flow or runoff volume in the final product - fortunately, the soils and average rainfall values that the model applied vary smoothly across any given region
    - it is therefore suggested that for coastal regions for which no data are available, the mean of the values in the neighbouring grid-cells (where data are available) can be taken but should be noted to be very uncertain - if a grid-cell is not adjacent to any cells with data, extend the region to one

which includes cells with observations; be aware that the performance of such values will be less and less accurate/certain as the region required increases

14. Summary and conclusions

14.1 Project summary

This project had a wide remit and has considered both statistical and design hydrograph approaches to flood estimation in small fluvial catchments, generally defined as less than about 25 km^2 in area but taken here to include larger catchment areas up to 41 km^2. The estimation of greenfield runoff rates and volumes in small plots has also formed part of the research.

A new data set of flood peaks for small catchments in the UK was developed and used as the basis for the main analyses. In addition, observed flood event data for a small number of catchments were used to investigate the shape of typical design hydrographs. Plot-scale flow data were used to compare methods for scaling flood peak estimates from small-catchment to plot-scale. Data from several rain gauges in England and Wales were used in a limited study of rainfall depth-duration-frequency relationships for short durations down to one minute.

14.2 Main results

Several new methodological developments were explored during the research, although not all were found to demonstrate substantial improvements and therefore were not recommended.

14.2.1 For current practice in small catchments

For estimating QMED the median annual flood, in small catchments, the following hierarchy is recommended: first, gauged peak flow data, if they are available, representative and of high-quality. Second, the QMED linking equation (Wallingford HydroSolutions 2016b), if daily mean flow data of sufficient length, representativeness and quality are available. Finally, the existing FEH catchment descriptor equation (Kjeldsen and others, 2008) is recommended for ungauged catchments or those with very poor quality or unrepresentative gauging. Only a single donor catchment should be used to adjust the ungauged QMED estimate if the target site is a small catchment; donors are not used when QMED is estimated from gauged at-site peak or gauged daily mean flow data.

For estimating floods other than QMED statistically: a modified selection method for defining pooling-groups for small and intermediate-sized catchments (up to 40 km^2) has been developed (see Section 8). This selection method applies equally to both enhanced single-site and ungauged analyses. Other aspects of the existing FEH pooling procedure (Kjeldsen and others, 2008), including the default distribution, size of the pooling-group and weighting of catchments within the pooling-group, are unchanged.

The ReFH2 design hydrograph method: this has been shown to generate flood event hydrograph shapes that are broadly appropriate, that is, similar to observed events for the majority of catchment types.

New guidance on applying seasonal design storms in urban catchments: this has been developed and these rules apply to all urban catchments of any size. In summary, summer storms should be used if URBEXT2000 ≥ 0.3, or if URBEXT2000 ≥ 0.15 and BFIHOST ≥ 0.65 and SAAR < 800 mm.

New guidance on using the urban model in ReFH2: in summary, the effects of urbanisation are not apparent for catchments with URBEXT2000 < 0.3, so the as-rural results should be generally used for catchments with URBEXT2000 < 0.3. However, accepting that urban adjustments are applied in the FEH statistical method for catchments with lower levels of urbanisation, the urbanised results can be used to provide precautionary estimates for catchments with 0.15 ≤ URBEXT2000 < 0.3. A Tp scaling factor of 1 should be used in this case.

A lower limit of one hour for hydrograph time-to-peak (Tp): currently applied in ReFH2, is justified and advantageous for applying in small catchments and at the plot scale.

14.2.2 For greenfield runoff and volume estimation in small plots

FEH methods (statistical and ReFH2) should be used to derive best estimates of greenfield runoff rates and volumes at the plot scale. Outdated methods such as IH124 and ADAS 345 should no longer be used.

Open-source data have been used to develop 1 km grids of estimated greenfield runoff rates and volumes for selected return periods, as well as runoff volume estimates for the 6-hour 100-year event for calculating long-term storage. These values have been derived by generalising the results of applying ReFH2 to a nominal 0.5 km^2 area at specified grid points across England and Wales. Although the results are not conservative, in that they cannot be guaranteed to provide underestimation of greenfield runoff rates and volumes at every point, they are less uncertain than the IH124 method on average. However, the data are intended for use as a preliminary screening tool only and are not intended to replace using the FEH methods described above.

14.2.3 Other analyses

Other analyses carried out during the project included an investigation of short duration rainfall depth-duration-frequency and a review of the value of local information on land management and catchment vegetation for flood estimation. Results from these studies are outlined in the relevant sections of this report and in separate technical reports.

14.2.4 Further guidance

Finally, attention is drawn to the suggestion that individual circumstances should always be considered when estimating flood frequency using generalised methods and recommendations should not be followed blindly. Hydrologists are recommended to consult the report ‘Making better use of local data in flood frequency estimation’ (Environment Agency 2017) for further general guidance on the types of local data that may be available, and how to use them.

14.3 Recommendations for further research

The first stage of this research project focused on identifying suitable peak flow records from small, gauged catchments in the UK. The review of data found that small catchments are not well represented in the National River Flow Archive (NRFA) peak flow data and this is particularly the case for small urban catchments. It is therefore recommended that these gauges should be reviewed as a priority and a list of 21 small, gauged catchments has been compiled to possibly include in future updates of the NRFA peak flow data set. In addition, the AMAX data for 34 gauges compiled by MacDonald and Fraser should also be reviewed.

Similarly, just three suitable gauges, with no more than three years of data each, were identified during this project on which to base all research and conclusions relating to plot-scale analysis. Commissioning only a few more well-placed and considered gauges on other plots of land will provide a relatively large data set to help verify the plot-scale analysis carried out in this project and significantly reduce the uncertainty associated with research on plot-scale runoff.

The analysis of short-duration rainfall data has highlighted the fact that data at a resolution of less than one hour were not available when the FEH13 rainfall depth-duration-frequency model was developed. Although FEH13 has been extrapolated to allow rainfall depth estimation for durations down to 15 minutes, further analysis of very short-duration data from throughout the UK would be beneficial.

Finally, the evaluation of the current design event method has highlighted that some of the assumptions in the method, particularly the use of single-peaked storm profiles, are worth further research.

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Project SC090031: List of reports

R1 Data collection

R2 Performance of FEH peak flow estimation methods in small catchments

R3 Summary of reassessment of FEH methods and recommendations

R4 Estimating the median annual flood (QMED) in small catchments

R5 Pooling-group formation for small catchments

R6 Estimating design hydrographs in small catchments

R7 Investigations of plot-scale runoff data

R8 Accounting for vegetation type and land management in flood estimation

R9 Depth-duration-frequency analysis for short-duration rainfall events

List of abbreviations

ADAS	Agricultural Development and Advisory Services – part of the former Ministry of Agriculture Fisheries and Food. ADAS 345 refers to ADAS Reference Book 345 (ADAS, 1982).
AEP	Annual exceedance probability. The chance that a flood of a given magnitude or larger will occur in any water year, normally expressed as a percentage.
AMAX	Annual maximum/annual maxima. A flood peak record that features only the largest event within each water year, with no lower limit on the magnitude of any event. Water years run from 1 October to the following 30 September.
AREA	AREA (in capitals) refers to the FEH digital catchment descriptor. This measures the area of a catchment according to the Integrated Hydrological Digital Terrain Model (IHDTM). All other catchment descriptors are based on the shape and boundary of the catchment as represented in the IHDTM.
BFIHOST	An FEH catchment descriptor, which estimates a catchment's baseflow index from the HOST classifications of the soils present.
CD3	A file format for storing FEH digital catchment descriptors, used by WINFAP-FEH. Can be exported from the FEH Web Service and FEH CD-ROM version 3.
DTM	Digital terrain model. The DTM in this report refers to the Integrated Hydrologic Digital Terrain Model (IHDTM). The IHDTM enforces drainage direction and flow paths according to rivers mapped by Ordnance Survey and Land & Property Services.
FARL	An FEH catchment descriptor measuring flood attenuation by reservoirs and lakes. Further information is given by Bayliss (1999).
FEH	Flood Estimation Handbook.
FEH13	Flood Estimation Handbook 2013. In this context, referring to the latest and current recommended (at time of study) model for design rainfall depths, published in the joint Defra/Environment Agency report 'Reservoir Safety – Long Return Period Rainfall' (Stewart and others, 2013).

FEH99	Flood Estimation Handbook 1999. In this context, referring to the 6-parameter model for design rainfall depths, published in Volume 2 of the FEH (Faulkner, 1999).
FPEXT	An FEH catchment descriptor measuring the fraction of a catchment that is estimated to be inundated by the 100-year flood. Further information is given by Kjeldsen and others (2008).
fse	Factorial standard error.
FSR	Flood Studies Report.
GLO	Generalised logistic distribution. The default distribution for AMAX series in the UK. A re-parameterised version of the log-logistic distribution (Ahmad and others, 1988).
HOST	Hydrology of soil types. A hydrologically-based classification and mapping of soils in the UK, in which every soil type is assigned to one of 29 classes. See Institute of Hydrology report 126 (Boorman and others, 1995) for further information.
IH	Institute of Hydrology.
MF	MacDonald and Fraser, referring to the QMED estimation method detailed in ‘An improved method for estimating the median annual flood for small ungauged catchments in the UK’ (MacDonald and Fraser, 2013)
NRFA	National River Flow Archive.
POT	Peaks-over-threshold. A flood peak record that features every independent flow maximum above a specified lower limit.
PROPWET	An FEH digital catchment descriptor. Measures the approximate fraction of time that soil moisture deficit within a catchment is less than 6 mm. Derivation of this descriptor is complex and described by Bayliss (1999).
QMED	Median annual flood, equivalent to the 2-year flood and the flood with AEP 50%. This is the index flood for the FEH statistical method.

QMED_{CD}	Estimate of QMED from catchment descriptors.
*Q*T (*Q*5, *Q*30, *Q*100, *Q*200)	T-year flood, equivalent to the flood with AEP (100/T)%. Section 7 only: daily mean flow exceeded on T percent of days.
ReFH1	The original revitalised flood hydrograph method. A rainfall-runoff flood estimation method, now superseded by ReFH2. Described in detail by Kjeldsen (2007).
ReFH2	The second version of the revitalised flood hydrograph method. The current rainfall-runoff flood estimation method in the UK. Described in Section 6.2.1 and in detail by Kjeldsen and others (2013) and Wallingford HydroSolutions (2016).
RMSD	Root-mean-square difference. An error statistic that is functionally identical to root-mean-square error. The term ‘difference’ is substituted for ‘error’ in comparing the QT estimation methods, as the benchmark values of QT are themselves estimates, therefore the tested methods cannot be said definitively to be in error if they simply do not match the benchmark values.
RMSE	Root-mean-square error.
SAAR	Standard-period annual average rainfall. An FEH catchment descriptor quantifying the mean annual total rainfall that fell in a catchment over the period 1961 to 1990.
UAF	Urban adjustment factor. A quantity, calculated from URBEXT_{2000} and BFIHOST, which is applied to an ungauged FEH statistical estimate of QMED. Its purpose is to increase the QMED estimate with urbanisation.
URBEXT (URBEXT_{1990}, URBEXT_{2000})	Urban extent. An FEH catchment descriptor that measures the fraction of urban development within a catchment. URBEXT_{1990} is based on urban areas identified in the Land Cover Map 1990, while URBEXT_{2000} is based on the Land Cover Map 2000. Both methods differentiate between urban and suburban land use, assuming

	that only half of a suburban area is developed. URBEXT$_{2000}$ also includes inland bare ground, assuming that it is between suburban and urban areas in terms of permeability.
WHS	Wallingford HydroSolutions. Developer, publisher and retailer of ReFH2 software, WINFAP-FEH, FEH Web Service and, previously, ReFH1 software.
WINFAP	Software to perform the FEH statistical method.

Appendix A: Stations used

The following tables show the names and catchment descriptors of the stations used in this project. Table 57 shows the names and catchment descriptors of all 152 catchments in the ‘high-quality’ data set, Table 58 shows the same for the 64 catchments in the ‘extended’ data set, and Table 59 shows the same for the one catchment removed from the ‘high-quality’ data set before the work described in Sections 7 and 8 (Reports R4 and R5) began. Due to space constraints, Table 57 starts on the next page.

Table 57 - ‘High-quality’ data set (152 catchments)

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
4009	Peffery	Strathpeffer STW	19	5.43	249250	858650	15.89	0.487	1060	0.973	0.0085	0.0378	152.4	
7009	Mosset Burn	Wardend Bridge	16	9.14	303950	855850	28.30	0.606	803	0.998	0.0000	0.0601	61.3	
13017	Colliston Burn	Colliston	21	3.37	360900	746650	8.40	0.546	750	0.996	0.0000	0.0678	35.9	
19010	Braid Burn	Liberton	38	3.81	327250	670750	15.39	0.514	770	0.947	0.1586	0.0326	113.8	
20002	West Peffer Burn	Luffness	49	3.53	348850	681150	26.31	0.471	616	0.996	0.0023	0.1279	30.4	✓
21001	Fruid Water	Fruid	15	19.10	308850	620700	22.17	0.392	1699	0.780	0.0000	0.0113	221.2	
21017	Ettrick Water	Brockhoperig	49	69.47	323400	613150	38.59	0.421	1740	1.000	0.0000	0.0120	241.5	✓
22003	Usway Burn	Shillmoor	28	19.22	388650	607750	21.87	0.302	1056	1.000	0.0000	0.0061	205.0	
23018	Ouse Burn	Woolsington	31	2.56	419550	570000	10.48	0.312	669	0.978	0.0975	0.1296	30.4	✓

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
24006	Rookhope Burn	Eastgate	20	24.62	395250	539050	36.62	0.293	1126	0.994	0.0001	0.0177	119.4	✓
25003	Trout Beck	Moor House	41	15.16	375900	533550	11.46	0.227	1904	1.000	0.0000	0.0412	91.9	✓
25011	Langdon Beck	Langdon	28	15.88	385200	530850	12.79	0.237	1463	1.000	0.0011	0.0125	123.4	
25012	Harwood Beck	Harwood	45	33.27	384950	530900	24.58	0.261	1577	1.000	0.0000	0.0212	121.0	✓
25019	Leven	Easby	36	5.54	458500	508650	15.07	0.525	830	1.000	0.0043	0.0194	128.0	✓
25808*	Burnt Hill	Moor House	8	0.08	375250	533300	0.75	0.294	1499	1.000	0.0000	0.0000	116.9	
25809*	Bog Hill	Moor House	9	0.07	377250	532650	0.05	0.228	1757	1.000	0.0000	0.0000	100.4	
25810*	Sike Hill	Moor House	6	0.09	377200	533200	0.04	0.275	1757	1.000	0.0000	0.0000	79.9	
26555	Ings Beck	South Newbald	15	0.54	490950	436100	14.20	0.985	704	1.000	0.0094	0.0083	73.7	
26802	Gypsey Race	Kirby Grindalythe	15	0.11	490400	467450	15.85	0.959	757	1.000	0.0000	0.0305	57.2	✓

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
26803	Water Forlornes	Driffield	15	0.44	502250	458250	32.43	0.949	721	1.000	0.0074	0.0159	65.4	✓
27010	Hodge Beck	Bransdale Weir	41	9.42	462750	494400	18.84	0.341	987	1.000	0.0007	0.0094	149.8	✓
27051	Crimple	Burn Bridge	42	4.54	428350	451900	8.15	0.309	855	1.000	0.0058	0.0133	62.9	✓
27073	Brompton Beck	Snainton Ings	34	0.81	493550	479450	8.06	0.887	721	1.000	0.0079	0.2373	47.7	✓
27081	Oulton Beck	Farrer Lane	28	2.36	436450	428100	25.10	0.535	677	0.997	0.2235	0.0486	40.4	✓
Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
28033	Dove	Hollinsclough	35	4.67	406350	366850	7.93	0.403	1346	1.000	0.0000	0.0075	166.9	✓
28041	Hamps	Waterhouses	29	26.66	408200	350250	36.97	0.301	1085	1.000	0.0041	0.0326	86.3	✓
28070	Burbage Brook	Burbage	57	4.29	425950	380350	8.45	0.426	1006	1.000	0.0000	0.0310	85.3	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
28115	Maun	Mansfield the Dykes	22	12.40	455950	363600	30.56	0.841	714	0.915	0.3886	0.0539	43.4	
29009	Ancholme	Toft Newton	40	1.83	503250	387650	29.52	0.625	616	0.997	0.0044	0.2063	12.2	
29013	Moor Beck	Clapgate Farm	29	0.22	496650	411100	7.10	0.797	637	0.984	0.0798	0.0863	25.0	
30013	Heighington Beck	Heighington	38	0.61	504150	369600	24.03	0.945	605	0.963	0.0790	0.1200	19.0	✓
30014	Pointon Lode	Pointon	42	2.61	512850	331250	10.94	0.338	591	1.000	0.0143	0.1046	29.0	
31023	West Glen	Easton Wood	42	1.88	496550	325800	4.32	0.32	641	1.000	0.0000	0.0516	32.8	
31025	Gwash South Arm	Manton	36	10.21	487550	305150	23.93	0.306	663	0.995	0.0064	0.0266	61.1	
31026	Egleton Brook	Egleton	36	1.14	487850	307350	2.30	0.533	645	1.000	0.0111	0.0936	41.0	
32029	Flore	Experimental Catchment	5	2.54	465550	260450	8.34	0.43	624	1.000	0.0016	0.0861	38.9	
33030	Clipstone Brook	Clipstone	7	10.94	493250	225550	40.35	0.362	640	0.975	0.0156	0.0824	34.0	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
33045	Wittle	Quidenham	46	1.16	602650	287750	27.55	0.534	608	0.974	0.0104	0.1771	15.1	
33048	Larling Brook	Stonebridge	32	0.30	592750	290650	21.99	0.694	635	0.907	0.0033	0.2331	8.8	
33052	Swaffham Lode	Swaffham Bulbeck	45	0.38	555300	262850	33.25	0.841	567	0.998	0.0121	0.2017	25.6	
33065	Hiz	Hitchin	21	0.35	518500	228950	12.00	0.968	621	1.000	0.0342	0.0475	58.0	
34051	Spixworth Beck	Spixworth	13	2.47	623750	316450	21.37	0.744	622	0.996	0.0390	0.1315	14.8	
36009	Brett	Cockfield	44	4.00	591400	252450	25.62	0.395	598	1.000	0.0052	0.1129	18.5	
36010	Bumpstead Brook	Broad Green	47	6.83	568950	241800	27.58	0.387	588	0.999	0.0075	0.0447	34.1	✓
36011	Stour Brook	Sturmer	47	6.38	569650	244050	34.28	0.382	592	0.999	0.1003	0.0603	33.5	✓
37033	Eastwood Brook	Eastwood	39	5.16	585850	188850	9.85	0.34	555	0.995	0.4113	0.0797	29.6	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT2000	FPEXT	DPSBAR (m/km)	Pooling?
37052	Prittlewell Brook	Prittlewell	15	1.24	583300	187000	6.36	0.38	559	1.000	0.3264	0.0543	28.4	
38007	Canons Brook	Elizabeth Way	64	7.00	543150	210350	20.74	0.352	601	0.988	0.2483	0.0520	29.3	
38012	Stevenage Brook	Bragbury Park	41	2.71	527450	221150	35.11	0.663	634	0.968	0.2806	0.0639	31.7	
38020	Cobbins Brook	Sewardstone Road	43	7.60	538650	199950	38.87	0.223	616	0.997	0.0517	0.0582	44.4	✓
Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT2000	FPEXT	DPSBAR (m/km)	Pooling?
39005	Beverley Brook	Wimbledon Common	50	11.14	521650	171750	39.49	0.476	630	0.994	0.4992	0.1379	26.6	✓
39017	Ray	Grendon Underwood	50	4.99	468050	221100	21.15	0.238	622	0.982	0.0037	0.1584	28.0	
39049	Silk Stream	Colindeep Lane	36	13.65	521700	189550	30.76	0.182	685	0.972	0.4014	0.0848	40.1	
39054	Mole	Gatwick Airport	53	10.10	526000	139800	32.33	0.437	816	0.943	0.1399	0.1719	33.5	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
39055	Yeading Brook West	North Hillingdon	20	4.24	508500	184500	16.82	0.172	657	0.999	0.5347	0.2032	16.1	✓
39082	Graveney	Longley Road	21	12.50	527850	170550	4.93	0.48	630	1.000	0.8110	0.2299	13.8	
39086	Gatwick Stream	Gatwick Link	39	9.75	528500	141750	32.63	0.597	830	0.946	0.1745	0.1036	47.9	
39092	Dollis Brook	Hendon Lane Bridge	57	7.36	524050	189450	23.72	0.178	689	0.991	0.3444	0.0466	49.4	
39095	Quaggy	Manor House Gardens	51	5.16	539450	174800	33.50	0.61	644	0.997	0.4780	0.0833	36.7	✓
39096	Wealdstone Brook	Wembley	38	11.95	519250	186250	23.45	0.175	664	0.997	0.5080	0.1333	25.7	
39126	Red	Redbourne	22	0.56	510450	211750	22.31	0.643	702	0.993	0.0909	0.0576	30.1	
39134	Ravensbourne East	Bromley South	21	4.85	540550	168650	9.80	0.685	680	0.993	0.4869	0.0678	24.9	
39135	Quaggy River	Chinbrook Meadows	13	0.98	541000	171950	14.50	0.715	674	0.998	0.3650	0.0526	43.2	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
39832	Wandle	Carshalton	34	0.74	527900	164750	0.90	0.855	668	1.000	0.6086	0.0418	33.8	
40021	Hexden Channel	Hopemill Bridge Sandhurst	32	12.75	581300	129000	32.06	0.406	778	1.000	0.0126	0.0347	76.0	
40555	Old Mill Stream Tributary East Stour	Aylesford Stream	10	3.35	602350	141250	17.96	0.686	753	0.991	0.0369	0.0922	38.3	
40556	Cradlebridge Sewer	Cradlebridge	10	3.16	594950	133700	5.80	0.248	712	1.000	0.0213	0.0953	36.7	
41020	Bevern Stream	Clappers Bridge	45	13.66	542250	116150	35.42	0.355	886	0.993	0.0128	0.0757	46.7	✓
41021	Clayhill Stream	Old Ship	45	4.07	544850	115300	7.10	0.252	805	1.000	0.0000	0.0509	27.2	
42017	Hermitage Stream	Havant	48	9.30	471050	106750	17.35	0.245	785	0.991	0.2380	0.0748	32.7	
43019	Shreen Water	Colesbrook	41	13.51	380750	127850	30.36	0.565	884	0.993	0.0152	0.0630	51.7	

Station No.	**Station**	**Watercourse**	**Record (years)**	**QMED (m^3/s)**	**Easting**	**Northing**	**AREA (km^2)**	**BFI-HOST**	**SAAR (mm)**	**FARL**	**URBEXT$_{2000}$**	**FPEXT**	**DPSBAR (m/km)**	**Pooling?**
43555	Brit	Beaminster RI	6	5.57	348000	101100	9.69	0.453	992	0.985	0.0459	0.0177	114.8	
44006	Sydling Water	Sydling St Nicholas	40	0.90	363250	99650	12.06	0.879	1030	0.944	0.0048	0.0162	128.9	
44008	South Winterbourne	Winterbourne Steepleton	35	0.45	362900	89750	20.17	0.811	1012	1.000	0.0043	0.0149	93.7	✓
44009	Wey	Broadwey	37	1.82	366600	83950	7.95	0.783	894	1.000	0.0225	0.0153	117.7	
Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
44013	Piddle	Little Puddle	21	3.04	371650	96800	31.27	0.889	1004	1.000	0.0043	0.0152	115.3	✓
44801	Hooke	Hooke	22	1.45	353850	99950	11.76	0.597	1030	0.923	0.0013	0.0183	81.0	
45816	Haddeo	Upton	21	3.52	298850	128900	6.81	0.59	1210	1.000	0.0050	0.0114	81.0	✓
45817	Unnamed Stream	Upton	21	1.36	298850	128950	1.74	0.603	1207	1.000	0.0022	0.0172	67.8	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
45818	Withiel Florey Stream	Bessom Bridge	22	4.26	298050	132600	9.85	0.578	1270	1.000	0.0000	0.0056	103.5	
46005	East Dart	Bellever	50	38.51	265700	77550	22.27	0.363	2095	1.000	0.0004	0.0420	95.0	✓
47009	Tiddy	Tideford	45	5.96	234400	59550	37.37	0.591	1276	1.000	0.0107	0.0237	121.2	✓
47021	Kensey	Launceston Newport	12	18.58	233000	85180	34.83	0.584	1298	0.998	0.0174	0.0218	101.3	✓
47022	Tory Brook	Newnham Park	21	7.33	255100	57650	13.45	0.431	1403	0.942	0.0141	0.0233	106.0	✓
48001	Fowey	Trekeivesteps	45	17.32	222650	69750	36.80	0.445	1636	0.938	0.0026	0.0435	92.4	✓
48004	Warleggan	Trengoffe	45	9.98	215900	67350	25.26	0.499	1445	0.978	0.0025	0.0350	93.8	✓
48005	Kenwyn	Truro	46	5.60	182050	45000	19.11	0.601	1100	0.988	0.0342	0.0096	90.4	
48006	Cober	Helston	30	5.49	165450	27250	40.83	0.671	1206	0.979	0.0189	0.0337	74.9	
48007	Kennal	Ponsanooth	46	4.24	176150	37650	26.83	0.736	1294	0.866	0.0103	0.0258	65.4	✓

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
48008	St Austell	Molingey	11	7.25	200700	49500	30.25	0.601	1272	0.961	0.0734	0.0343	111.0	
48009	St Neot	Craigshill Wood	12	8.47	218400	66150	22.91	0.463	1512	0.982	0.0023	0.0224	78.2	✓
48555	Allen (Truro)	Idless	17	6.08	182300	47300	24.48	0.616	1081	1.000	0.0055	0.0198	86.5	
48556	Par	Luxulyan	17	6.91	204350	58200	25.75	0.541	1385	0.972	0.0312	0.1169	54.7	
48801	Cober	Trenear	27	2.40	167550	31050	26.53	0.672	1265	0.976	0.0040	0.0351	65.0	
49003	De Lank	De Lank	48	13.99	213350	76550	21.61	0.379	1628	0.998	0.0000	0.0636	76.0	✓
49005	Bollingey Stream	Bolingey Cocks Bridge	4	6.52	176850	52900	16.08	0.627	1044	0.991	0.0060	0.0229	81.4	✓
49006	Camel	Camelford	8	9.12	210650	83850	12.86	0.576	1418	1.000	0.0042	0.0122	57.5	✓
49555	Valency	Boscastle Anderton Ford	8	6.99	214150	91150	5.53	0.534	1327	1.000	0.0106	0.0063	76.5	
49556	Coastal Stream	Port Isaac	8	0.42	199800	80400	2.77	0.503	999	1.000	0.0144	0.0027	135.3	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
51002	Horner Water	West Luccombe	33	10.60	289800	145850	20.38	0.539	1485	0.978	0.0001	0.0028	213.9	✓
Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
51003	Washford	Beggearn Huish	47	6.12	304000	139450	36.70	0.588	1151	0.982	0.0028	0.0048	194.4	✓
52015	Land Yeo	Wraxall Bridge	35	3.41	348300	171550	23.33	0.669	906	0.933	0.0167	0.0579	73.3	
52016	Currypool Stream	Currypool Farm	44	2.68	322050	138200	15.70	0.586	934	1.000	0.0000	0.0375	133.8	
52025	Hillfarrance Brook	Milverton	22	10.67	311350	127000	27.75	0.633	1009	0.996	0.0141	0.0230	135.5	
52026	Alham	Higher Alham	29	1.44	367950	140900	4.90	0.61	1006	1.000	0.0041	0.0071	90.0	
54022	Severn	Plynlimon Flume	37	15.03	285250	287200	8.69	0.323	2483	1.000	0.0000	0.0098	180.2	✓
54026	Chelt	Slate Mill	23	9.42	389150	226450	31.31	0.443	726	0.975	0.2049	0.1034	79.5	
54091	Severn	Hafren Flume	34	5.92	284350	287650	3.48	0.303	2514	1.000	0.0000	0.0122	159.2	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
54092	Hore	Hore Flume	34	6.35	284550	287250	3.19	0.33	2531	1.000	0.0000	0.0015	214.5	
54555	Bow Brook	Feckenham	12	8.92	400500	261150	22.44	0.365	690	0.980	0.0837	0.0491	52.1	
55010	Wye	Pant Mawr	56	50.40	284300	282550	27.18	0.386	2341	1.000	0.0000	0.0183	211.8	
57010	Ely	Lanelay	41	41.06	303350	182650	38.90	0.455	1620	1.000	0.0340	0.0444	117.9	
57017	Rhondda Fawr	Tynewydd	13	24.30	293250	198650	16.64	0.317	2458	0.999	0.0156	0.0117	217.4	✓
60012	Twrch	Ddol Las	37	13.39	265050	243950	19.50	0.419	1531	1.000	0.0025	0.0324	161.0	
64011	Cerist	Llawr Cae	18	5.37	281950	316300	5.35	0.459	2159	1.000	0.0000	0.0037	433.3	
65005	Erch	Pencaenewydd	42	10.85	240000	340450	19.39	0.439	1477	0.991	0.0012	0.0711	96.0	
67010	Gelyn	Cynefail	41	16.42	284350	341950	12.87	0.251	2000	0.969	0.0000	0.0322	127.8	
67013	Hirnant	Plas Rhiwedog	12	24.08	294600	334950	32.47	0.415	1756	1.000	0.0000	0.0182	222.9	
68010	Fender	Ford Lane	9	5.54	328050	388000	18.00	0.432	774	0.999	0.2078	0.1024	29.0	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
68011	Arley Brook	Gore Farm	6	6.09	369650	379900	33.76	0.437	831	0.998	0.0212	0.2498	12.4	
68021	Arrowe Brook	Acton Lane	8	4.45	325500	389300	17.87	0.513	750	0.996	0.1735	0.1385	24.8	✓
69019	Worsley Brook	Eccles	25	5.74	375300	397950	24.09	0.349	956	0.941	0.3450	0.2202	22.1	
69042	Ding Brook	Naden Reservoir	21	1.58	385000	417450	2.18	0.401	1488	1.000	0.0000	0.0138	139.9	
69046	Bradshaw Brook	Bradshaw Tennis Club	14	23.50	373300	412200	36.87	0.345	1384	0.781	0.0234	0.0223	101.2	
69047	Roch	Littleborough	21	8.25	394000	416500	14.80	0.475	1353	0.890	0.0354	0.0384	138.5	✓
71003	Croasdale Beck	Croasdale Flume	18	10.07	370650	454650	10.71	0.276	1882	1.000	0.0000	0.0160	156.8	✓
Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
71013	Darwen	Ewood	41	27.57	367700	426250	39.08	0.424	1340	0.938	0.1393	0.0356	95.1	✓

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
72007	Brock	U/S A6	34	31.41	351150	440550	31.53	0.319	1361	1.000	0.0000	0.0535	108.8	✓
72014	Conder	Galgate	47	17.70	348150	455350	28.99	0.443	1183	0.975	0.0064	0.0822	93.4	✓
72817	New Mill Brook	Hollowforth Hall	30	20.51	350350	436350	33.19	0.387	1110	0.992	0.0212	0.0930	35.8	
73006	Cunsey Beck	Eel House Bridge	41	7.66	336950	494050	18.77	0.448	1897	0.727	0.0022	0.0522	119.2	
73009	Sprint	Sprint Mill	45	42.55	351450	496100	34.80	0.453	2011	0.997	0.0000	0.0612	224.3	✓
73015	Keer	High Keer Weir	21	12.24	352250	471900	30.06	0.486	1158	0.976	0.0029	0.0746	83.0	✓
76001	Haweswater Beck	Burnbanks	35	18.22	350850	515950	32.34	0.345	2438	0.645	0.0000	0.0154	293.6	✓
76011	Coal Burn	Coalburn	37	1.84	369350	577750	1.63	0.196	1096	1.000	0.0000	0.0736	47.2	✓
76811	Dacre Beck	Dacre Bridge	14	53.01	346050	526300	33.97	0.457	1428	0.999	0.0000	0.0724	101.4	✓
80003	White Laggan Burn	Loch Dee	33	6.60	246800	578050	5.70	0.385	2469	0.996	0.0000	0.0168	246.3	

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
80005	Dargall Lane	Loch Dee	28	4.10	245050	578700	2.07	0.355	2435	1.000	0.0000	0.0230	307.5	
84002	Calder	Muirshiel	21	16.31	230900	663750	12.06	0.271	2316	0.988	0.0000	0.0398	95.2	
84016	Luggie Water	Condorrat	46	24.35	273950	672550	35.32	0.327	1089	0.995	0.0658	0.0526	56.0	✓
84023	Bothlin Burn	Auchengeich	42	8.63	267800	671600	34.85	0.313	1029	0.912	0.0940	0.1365	38.4	✓
84026	Allander Water	Milngavie	41	36.01	255800	673750	30.36	0.369	1424	0.896	0.0404	0.0501	101.3	
84029	Cander Water	Candermill	37	20.52	276400	647000	25.50	0.399	1033	0.985	0.0165	0.0419	52.9	
86001	Little Eachaig	Dalinlongart	42	42.83	214250	682050	31.84	0.393	2340	1.000	0.0005	0.0270	277.6	
89004	Strae	Glen Strae	29	60.11	214650	729400	37.38	0.362	2766	0.995	0.0000	0.0468	324.4	✓
101005	Eastern Yar	Budbridge	31	4.70	453050	83450	24.28	0.707	841	0.996	0.0193	0.0458	87.1	
203046	Rathmore Burn	Rathmore Bridge	32	10.82	319750	385350	22.51	0.43	1043	1.000	0.0000	0.0726	57.8	✓
203049	Clady	Clady Bridge	32	23.24	319950	383750	29.38	0.367	1079	1.000	0.0000	0.0599	58.1	

Station No.	**Station**	**Watercourse**	**Record (years)**	**QMED (m^3/s)**	**Easting**	**Northing**	**AREA (km^2)**	**BFI-HOST**	**SAAR (mm)**	**FARL**	**URBEXT$_{2000}$**	**FPEXT**	**DPSBAR (m/km)**	**Pooling?**
205034*	Woodburn	Control	11	0.12	337300	390050	5.74	0.41	1177	0.901	0.0000	0.0514	53.9	
205101	Blackstaff	Eason's	22	9.86	331750	372400	14.15	0.414	990	0.997	0.4192	0.1657	54.2	
206004	Bessbrook	Carnbane	30	10.59	307400	329250	34.76	0.584	1055	0.917	0.0204	0.0441	97.3	
206006	Annalong	Recorder	48	15.33	334800	323350	13.66	0.336	1720	0.980	0.0000	0.0236	275.8	✓

Table 58 - ‘Extended’ data set (64 catchments – none suitable for pooling)

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)
4063	Pyl Brook	West Barnes Lane (Kings College)	11	6.50	523200	167950	17.34	0.556	652	0.995	0.5423	0.0873	28.9
4186	Graveney	Stretham (Abercarne Road)	11	7.00	529250	170300	12.14	0.332	648	1.000	0.7663	0.1336	31.4
15002	Newton Burn	Newton	24	6.91	323000	760550	16.65	0.461	1200	1.000	0.0000	0.0153	198.5
15004	Inzion	Loch of Lintrathen	44	6.41	327950	755850	24.49	0.529	1081	0.997	0.0000	0.0292	187.4
15027	Garry Burn	Loakmill	16	7.54	307450	733950	22.57	0.574	947	0.999	0.0116	0.0591	110.9
15809	Muckle Burn	Eastmill	20	7.63	322300	760450	16.69	0.481	1132	0.960	0.0000	0.0196	160.8
17012	Red Burn	Castle Cary	20	20.10	278800	678050	21.74	0.329	1172	0.995	0.1392	0.1097	55.4
18020	Loch Ard Burn	Duchray	12	1.35	246800	698700	0.86	0.609	2000	1.000	0.0000	0.0058	155.8
27038	Costa Beck	Gatehouses	42	1.38	477600	483800	7.98	0.774	722	0.990	0.0220	0.1253	36.0
27047	Snaizeholme Beck	Low Houses	34	13.22	383300	488250	10.93	0.304	1733	0.977	0.0000	0.0208	204.2

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)
27082	Cundall Beck	Bat Bridge	17	7.02	441950	472350	22.96	0.654	635	0.999	0.0175	0.2062	14.8
27852	Little Don	Langsett Reservoir	22	19.27	421300	400400	21.13	0.32	1316	0.846	0.0013	0.0074	122.3
33064	Whaddon Brook	Whaddon	15	0.25	535900	246650	14.56	0.943	558	0.997	0.1171	0.1492	24.1
33813	Mel	Meldreth	17	0.55	537800	246550	4.86	0.886	552	0.996	0.0346	0.1743	21.6
38014	Salmon Brook	Edmonton	53	5.52	534350	193750	22.85	0.258	665	0.978	0.2926	0.0562	48.3
39036	Law Brook	Albury	17	0.55	504550	146750	16.05	0.888	819	0.960	0.0084	0.0173	85.7
39116	Sulham Brook	Sulham	16	0.70	464200	174050	3.03	0.408	657	1.000	0.0017	0.2409	46.0
39813	Mol	Ifield Weir	10	3.23	524450	136350	13.08	0.675	827	0.890	0.1972	0.0911	42.4
39830	Beck	Rectory Road	7	2.06	536800	169900	9.15	0.728	673	0.937	0.5249	0.0599	25.9
39831	Chaffinch Brook	Beckenham	7	2.17	535950	168500	9.29	0.597	673	1.000	0.4980	0.0760	32.7
40809	Pippingford Brook	Paygate	17	9.20	547950	134300	24.16	0.413	859	0.913	0.0061	0.0182	92.8

Station No.	**Station**	**Watercourse**	**Record (years)**	**QMED (m^3/s)**	**Easting**	**Northing**	**AREA (km^2)**	**BFI-HOST**	**SAAR (mm)**	**FARL**	**URBEXT$_{2000}$**	**FPEXT**	**DPSBAR (m/km)**
41001	Nunningham Stream	Tilley Bridge	33	11.00	566150	112850	16.79	0.378	804	1.000	0.0131	0.0664	67.6
41016	Cuckmere	Cowbeech	45	8.72	561150	115050	19.10	0.471	855	0.966	0.0273	0.0434	78.5
Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)
41028	Chess Stream	Chess Bridge	48	6.84	521750	117300	24.92	0.497	849	0.983	0.0135	0.0971	47.0
41037	Winterbourne Stream	Lewes	37	0.46	540300	109550	17.41	0.966	904	1.000	0.0098	0.0074	124.4
41801	Hollington Stream	Hollington	6	2.03	578800	110050	3.47	0.366	781	1.000	0.4094	0.0094	83.4
41806	North End Stream	Allington	15	0.72	538450	113800	2.37	0.646	929	1.000	0.0000	0.0211	130.3
42019	Tanners Brook	Millbrook	31	3.47	438800	113250	14.15	0.368	793	0.978	0.2498	0.0408	56.3
42020	Tadburn Lake Stream	Romsey	28	3.01	436250	121250	19.61	0.607	782	0.983	0.0537	0.0630	48.4
44807	Win	Winfrith	9	1.20	380550	84900	16.78	0.786	894	1.000	0.0047	0.0150	108.5

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	URBEXT$_{2000}$	FPEXT	DPSBAR (m/km)
45006	Quarme	Enterwell	9	9.76	291950	135550	20.03	0.514	1419	1.000	0.0008	0.0095	153.9
46801	Erme	Erme	9	23.37	264000	63250	15.25	0.257	2110	0.992	0.0000	0.0389	74.9
46806	Avon	Avon Intake	17	24.73	268050	64100	13.84	0.37	2152	0.903	0.0000	0.0381	90.9
47016	Lumburn	Lumburn Bridge	13	7.02	245900	73250	20.58	0.597	1285	1.000	0.0044	0.0145	83.8
47025	Wolf	Germansweek	21	11.49	244550	94250	11.34	0.411	1188	1.000	0.0007	0.0066	78.1
47804	Hennard Stream	Moors Mill	14	7.62	242450	93850	7.17	0.398	1150	1.000	0.0000	0.0059	67.3
50009	Northlew	Norley Bridge	24	18.51	250150	99950	20.16	0.446	1195	1.000	0.0014	0.0231	77.3
52020	Gallica Stream	Gallica Bridge	8	20.28	357050	109950	16.61	0.389	950	0.971	0.0014	0.0181	86.4
54060	Potford Brook	Sandyford Bridge	26	2.38	363600	322000	22.37	0.645	677	0.998	0.0013	0.1328	24.7
54062	Stoke Brook	Stoke	13	0.45	363750	328000	10.92	0.757	698	0.939	0.0224	0.0985	26.3
54087	Allford Brook	Childs Ercall	21	0.17	366650	322750	2.92	0.863	663	1.000	0.0000	0.1083	15.2
54090	Tanllwyth	Tanllwyth Flume	28	2.27	284250	287650	1.10	0.328	2462	1.000	0.0000	0.0080	155.0

Station No.	**Station**	**Watercourse**	**Record (years)**	**QMED (m^3/s)**	**Easting**	**Northing**	**AREA (km^2)**	**BFI-HOST**	**SAAR (mm)**	**FARL**	**$URBEXT_{2000}$**	**FPEXT**	**DPSBAR (m/km)**
54097	Hore	Upper Hore Flume	14	3.90	283150	286900	1.61	0.303	2649	1.000	0.0000	0.0031	224.3
55015	Honddu	Tafalog	29	16.68	327700	229350	24.93	0.573	1315	1.000	0.0000	0.0066	257.1
55033	Wye	Gwy Flume	33	8.93	282450	285350	3.84	0.33	2575	1.000	0.0000	0.0156	200.4
55035	Iago	Iago Flume	15	1.85	282500	285400	1.01	0.335	2461	1.000	0.0000	0.0025	186.6
58010	Hepste	Esgair Carnau	24	11.92	296950	213350	10.94	0.261	2079	1.000	0.0000	0.0397	78.4
65008	Nant Peris	Tan-Yr-Alt	21	33.60	260850	357950	10.32	0.548	3465	0.996	0.0000	0.0444	487.9
Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)
66801	Upper Conway	Blaen y Coed	6	14.68	280450	345100	11.73	0.228	2196	0.911	0.0000	0.0541	83.8
67003	Llyn Brenig	Llyn Brenig Outflow	10	15.28	297450	353850	22.45	0.319	1317	0.587	0.0000	0.0182	72.2
68014	Sandersons Brook	Sandbach	5	1.45	375350	365250	3.77	0.394	742	0.986	0.0229	0.1597	13.3
69034	Musbury Brook	Helmshore	8	5.02	377450	421250	3.03	0.345	1454	1.000	0.0000	0.0083	159.4

Station No.	**Station**	**Watercourse**	**Record (years)**	**QMED (m^3/s)**	**Easting**	**Northing**	**AREA (km^2)**	**BFI-HOST**	**SAAR (mm)**	**FARL**	**URBEXT$_{2000}$**	**FPEXT**	**DPSBAR (m/km)**
71005	Bottoms Beck	Bottoms Beck Flume	14	15.52	374500	456550	10.58	0.28	1511	0.999	0.0000	0.0459	90.8
73803	Winster	Lobby Bridge	12	8.46	342350	488550	22.03	0.538	1508	0.991	0.0000	0.0608	119.2
80004	Green Burn	Loch Dee	22	4.15	248050	579050	2.62	0.365	2383	0.998	0.0000	0.0172	189.9
84034	Auldhouse Burn	Spiers Bridge	15	6.20	254600	659050	17.17	0.478	1329	0.924	0.1761	0.0771	56.7
84035	Kittoch Water	Waterside	15	19.10	259600	656200	16.80	0.337	1184	0.978	0.2647	0.0525	56.8
84036	Earn Water	Letham	15	15.80	256650	654850	20.89	0.431	1481	0.908	0.0005	0.0528	75.9
87801	Allt Uaine	Intake	20	8.50	226250	711300	2.89	0.358	3473	1.000	0.0000	0.0087	368.6
89007	Abhainn a' Bhealaich	Braevallich	25	40.22	195700	707600	23.60	0.303	2488	0.923	0.0000	0.0426	128.6
91802	Allt Leachdach	Intake	34	6.35	226150	778100	6.52	0.397	2555	0.992	0.0000	0.0031	407.5
102001	Cefni	Bodffordd	16	9.60	242900	376850	21.01	0.448	1061	0.964	0.0007	0.1029	29.0
203038	Rocky	Rocky Mountain	18	10.80	324300	326550	6.80	0.327	1610	1.000	0.0000	0.0162	213.1

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)
205015	Cotton	Grandmere	13	2.80	352450	381750	22.53	0.489	863	0.998	0.0765	0.2169	24.3

Table 59 - Stations included in report R2: Performance of FEH methods but excluded from model development reports R4 and R5

Station No.	Station	Watercourse	Record (years)	QMED (m^3/s)	Easting	Northing	AREA (km^2)	BFI-HOST	SAAR (mm)	FARL	$URBEXT_{2000}$	FPEXT	DPSBAR (m/km)	Pooling?
27032	Hebden Beck	Hebden	48	3.92	402550	464350	22.20	0.252	1433	0.997	0.0000	0.0207	99.1	✓

Appendix B: Greenfield plot-scale peak flow rate and volume screening data

Free plot-scale peak flow rates and volume data sets are provided as part of Project SC090031 ‘Estimating flood peaks and hydrographs for small catchments’ (Phase 2). The data are 1 km raster grids of estimated plot-scale peak flow rate (l/s/ha) across England and Wales for return periods of 12 months, two years, 30 years and 100 years (note that a 12-month return period on the peaks-over-threshold scale equates to approximately a 1.58-year return period on the annual maximum scale). The data set also includes estimated values for peak flow rate (l/s/ha) and runoff volume (m^3) corresponding to a 6-hour 100-year return period rainfall event.

This appendix outlines the data provided and some guidelines for usage.

Information Warning

These estimates of peak flow rates and runoff volume are on average more conservative than the FEH ReFH2 method, that is, they are biased towards underestimating greenfield peak flow rates and runoff volume. However, conservative estimates cannot be guaranteed for any individual point, and therefore the data should only be used for preliminary screening and to provide precautionary results to use at the pre-planning stage of new developments. It is recommended that using the data should be followed by using the latest and recommended FEH ReFH-FEH hydrological design package.

A2.1 Data specifications

- the gridded outputs consist of six ASCII gridded data sets at 1 km resolution, outlined in Table 60
- the cell **centres** lie on 1,000 m increments of the GB National Grid
- the grid extends from eastings -500 m to 699500 m, northings -500m to 1299500m
- cells outside England and Wales have the no-data value -9999
- estimated runoff rates are given in l/s/ha and estimated volume in m^3

Table 60: Files available as part of project

Filename	Description
Q1MAP_projected.asc	12-month return period peak flow rate
Q2MAP_projected.asc	2-year return period peak flow rate
Q30MAP_projected.asc	30-year return period peak flow rate
Q100MAP_projected.asc	100-year return period peak flow rate
Q6H100Y_projected.asc	6-hour 100-year return period peak flow rate
ROVOL6H100Y_projected.asc	6-hour 100-year return period runoff volume

A2.2 Usage guidelines

For small plot-scale sites, the value of the closest grid cell centroid should be selected. Interpolation methods may not give a more reliable answer than simply taking the closest value. If an interpolation scheme is used, a simple inverse-distance scheme would be appropriate. To use this method, identify the values for up to four grid posts nearest to the site centroid. Identify the distance from the site centroid to each grid post and take an inverse-distance weighted average of the grid post values. This is suitable for a site much less than 50 ha in size. For larger sites, users should make their own judgement about the spatial variation in runoff rates across the site based on local information on soils.

A2.3 Accessing the greenfield plot-scale peak flow rate and volume data

The greenfield runoff screening data can be downloaded from the project page on Gov.uk.

Would you like to find out more about us or your environment?

Then call us on

03708 506 506 (Monday to Friday, 8am to 6pm)

Email: enquiries@environment-agency.gov.uk

Or visit our website

www.gov.uk/environment-agency

incident hotline

0800 807060 **(24 hours)**

floodline

0345 988 1188 **(24 hours)**

Find out about call charges (https://www.gov.uk/call-charges)

Environment first

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