Estimating flood peaks and hydrographs for small catchments:

R6 – Estimating design hydrographs in small catchments

FCERM Research & Development Programme

Research Report

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Executive summary

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. This report presents details of three separate analyses related to estimating design hydrographs in small catchments and plots.

Section 1 gives details of a study which 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). The latter method was selected as a readily available empirical hydrograph method and was used to compare with ReFH2. The report focuses on a selection of small catchments and compares the two methods, highlighting differences between the two and offering hydrological justification. Uncertainty in the methods from sampling and model error is discussed and highlighted as an area of improvement from improved models and using longer gauge records.

The main findings are that in essentially rural and impermeable catchments, the two methods agree well. The ReFH2 model seems to be less representative in highly urban (when used with default urban parameters) or highly permeable catchments. This is a common issue with simple conceptual rainfall-runoff models but using more complex modelling frameworks is not a viable option since it is compromised by the lack of available data to describe the complex runoff generation processes in these catchment types.

The empirical median hydrograph has increased uncertainty when the length of the records chosen is short or the size of individual flood observation windows does not encapsulate the whole storm event. This is a limitation for applying the method to highly urbanised and/or groundwater-dominated catchments. The peak-detection software, developed by the National University of Ireland and used to highlight events in the EMH method, is criticised due to poor identification of true flood events. This may be due to the software not performing well in highly permeable or urban catchments with extreme responses to rainfall events. For lower percentile widths where fewer events have data recorded, the EMH can suffer from non-monotonic kinks (i.e. “fold back” on itself, resulting in two values at the same time, some examples of which can be seen in Section 1.4); in practice, these duplicate values are either omitted or smoothing is applied. Overall, the methods seem to be in agreement for most of the catchments in the study given limitations in sample size and model specification for urban and permeable catchments.

This outcome confirms that ReFH2 hydrographs and using the recommended duration are appropriate for most catchment types. The limitations of both methods are exposed in difficult hydrological cases such as highly urbanised or groundwater catchments, and, in these catchments, great care is needed to obtain the best modelling outcome recognising the limitations of all methods.

Section 2 of the report reviews the current recommendations for seasonal design inputs to the ReFH2 method which are linked to the extent of catchment urbanisation. The implications of the analysis have been condensed into a set of rules for selecting when summer storms should be used within ReFH2 as follows:

- if $URBEXT_{2000}$ is ≥ 0.30 (that is, the catchment is very heavily urbanised), summer storms using either the 75% storm profile or 50% summer profile should be used
- if $0.15 \leq URBEXT_{2000} < 0.3$ (moderately urbanised) and BFIHOST ≥ 0.65 and SAAR < 800 mm a summer storm should be used - 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
- in all other cases winter storms should be used

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.

The final section of this report follows on from the analysis of plot-scale runoff in an earlier part of the project. It reviews the evidence for imposing a lower limit of Tp of one hour in small catchments and plots. 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 plot-scale runoff estimation, the results suggest that it is appropriate to limit Tp to one hour as this will provide a conservative (low) estimate of the allowable rate of discharge from a development site.

Important Note:

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

1. Hydrograph shape analysis

1.1 Introduction

Design flood hydrographs are an important part of flood frequency estimation, complementing the statistical method of estimating expected peak flow for given return periods using the index flood method. 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.

This section compares 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 is important to note that the empirical method was used to provide a data-based context to the ReFH2-derived hydrograph shapes. It should also be noted that Archer’s method is only one such empirical method. It was selected for this analysis as it is a recognised method and there were existing catchment analyses available to the project that had been developed using this method. The purpose of this study has not been to make recommendations regarding the efficacy or use of empirical hydrograph shapes.

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

1.2 Review of methods

ReFH2 method

Version 2 of the revitalised FSR/FEH rainfall-runoff method (ReFH2), as defined in Wallingford HydroSolutions (2015) and implemented in the ReFH2 software, is an extension to the original ReFH method as described in FEH Supplementary Report No. 1 (Kjeldsen 2007). In the ReFH2 software, design hydrographs are calculated for flood events of a given return period, T, based on the instantaneous ‘kinked’ unit hydrographs defined in Kjeldsen (2007), along with a baseflow model, a loss model and the FEH13 rainfall model (Stewart and others, 2013). The final hydrograph shape is obtained by combining the unit hydrograph with the profile of effective rainfall to obtain the design flood hydrograph. Although ReFH2 has been calibrated to use with both the FEH99 and the FEH13 rainfall models, the FEH13 model is recommended. This gives a model shape based on estimating four basic model parameters (maximum soil moisture capacity, unit hydrograph time-to-peak, baseflow lag and baseflow recharge) and two initial conditions (soil moisture and baseflow) estimated from appropriate gauged data or catchment descriptors. The method also incorporates guidance on catchment urbanisation and flood seasonality which introduce further model parameters.

Empirical median hydrograph

This method follows that of Archer and others (2000) and has been used in the Irish Flood Studies Update (O'Connor and others, 2014). The method derives the shape of the total flow curve directly from summary statistics of a series of events at a given catchment. In this case, the largest peak flows for a given catchment over the length of the record are considered. For each event, the duration for which the flow exceeds a given percentage p of peak flow is computed for each of the rising and receding limbs relative to the time at the point of peak flow. For each percentage p, the median ‘duration-of-exceedance value’ (DOE_p) is determined for each limb, and a non-dimensional empirical median hydrograph (EMH) shape is determined. Archer and others (2000) tried using the mean duration but found this could be unduly influenced by individual, very long-duration outlier events.

This method can be simplified by assuming that the hydrograph is symmetric about the peak for sufficiently high values of p, and computing a single value for DOE_p using the data from both limbs at each event. Such an assumption of symmetry should be assessed before using this simplification, but was offered as a suggestion in Section 10.4 of FEH Volume 3 (Robson and Reed 1999) for estimating hydrograph shape as an alternative to the rainfall-runoff method.

It should be noted that no other aspects, such as a rainfall profile or antecedent conditions, are considered in this model, only the observed total flow. Specific design hydrographs can be obtained by scaling to the desired peak flow derived either from flood frequency curves or catchment descriptors. Note that this method only considers total flow, and baseflow is not differentiated.

The EMH method shows how the mean or median width of the hydrograph varies against the percentile of the peak, and so (because of variations in sample sizes between different percentiles) there is no requirement for this to show only one flow value for a particular time step. The basic approach is illustrated in Figure 1.

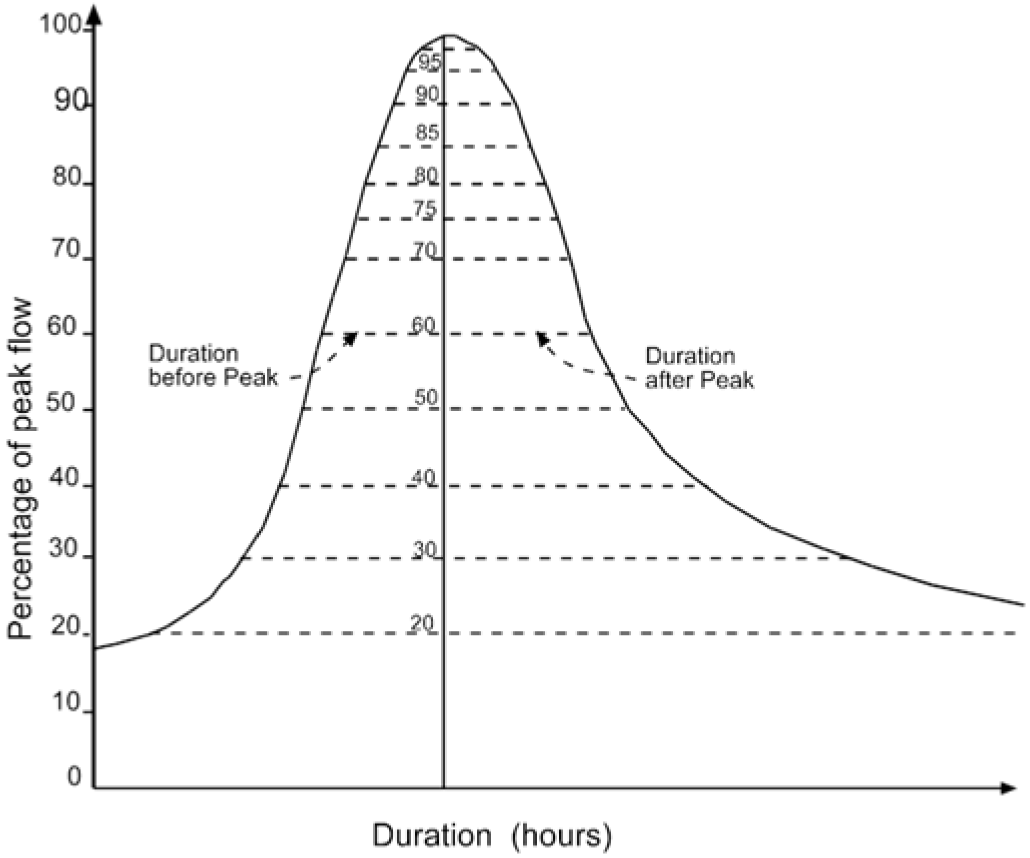


Figure 1 - The empirical median hydrograph method: identifying the median width of a hydrograph

Figure 1 illustrates the EMH method. The y-axis shows the percentage of peak flow (from 0 to 100). The x-axis shows the duration in hours (increasing from left to right).

1.3 Review of data

Choice of catchments

21 catchments were initially chosen for hydrograph shape analysis covering a range of catchment response times (Tp), levels of urbanisation ($URBEXT_{2000}$) and values of baseflow index (BFIHOST) from those catchments under 40.9 km^2 which were suitable for estimating hydrographs and for which either the Environment Agency, Scottish Environment Protection Agency (SEPA) or Natural Resources Wales (NRW) had gauged data. None of the chosen catchments had a value of reservoir flood attenuation FARL < 0. 94, that is, these are catchments without significant open water bodies within the contributing area. This was to avoid needing to explicitly model the attenuation since ReFH doesn’t represent such effects. The chosen catchments are listed in Table 1.

For the ReFH2 model, catchment descriptors and FEH13 rainfall parameters were obtained from the FEH Web Service (Centre for Ecology & Hydrology, 2015), using data from the full length of records available.

Choice of events

For each catchment, the top 20 peak flows over the length of the catchment's record were used to compute the EMH. This data was derived from automatic peak detection software built into the Hydrograph Width Analysis (HWA) software developed by the National University of Ireland, Galway (Duncan Faulkner pers comm.). These peaks were checked visually, and then any unsuitable peaks were removed from the median calculation. Events were typically excluded as a result of having multiple peaks, or the event being barely distinguishable from the baseflow. Despite this, some events were kept despite having substantial secondary peaks, or having the peak of the event incorrectly identified by the HWA software. These incorrect peaks have been kept as demonstration of the complete EMH method.

Once such events had been selected, 15-minute data was analysed over a predetermined duration before and after the peak, these durations kept constant over events in the same catchment. To obtain better readings of baseflow response, some catchments used an extremely long time window. For example, many catchments adopted a window of six hours before to eight hours after, but in the Heighington catchment 720 hours before and 960 hours after peak flow were used.

Due to a lack of satisfactory flood events within the record for the Carshalton catchment, this was ultimately removed from the analysis, as the events appeared to be extremely brief spikes superimposed on baseflow.

Table 1- List of gauging stations used

Gauging Station	AREA [km^2]	BFIHOST	URBEXT$_{2000}$	Record [years]	Events used	Notes
Bromley South	9.8	0.685	0.4869	21	20	n/a
Carshalton	0.9	0.855	0.6086	34	2	Gauge excluded
Chinbrook Meadows	14.5	0.715	0.3650	13	15	n/a
Clipstone	40.35	0.362	0.0156	7	15	Jul 2001 removed
Egleton	2.3	0.533	0.0111	36	20	n/a
Galgate	28.99	0.443	0.0064	47	20	n/a
Gatwick Airport	32.33	0.437	0.1399	53	17	n/a
Grendon Underwood	21.15	0.238	0.0037	50	18	n/a
Heighington	24.03	0.945	0.0790	38	19	Long time window
Higher Alham	4.9	0.610	0.0041	29	11	Smaller peaks removed
Hitchin	12.0	0.968	0.0342	21	17	Jul-Aug 2002 removed
Hollinsclough	7.93	0.403	0	35	16	n/a
Launceston Newport	34.83	0.584	0.0174	12	20	n/a

Gauging Station	AREA [km^2]	BFIHOST	URBEXT$_{2000}$	Record [years]	Events used	Notes
Llawr Cae	5.35	0.459	0	18	14	n/a
Longley Road	4.93	0.480	0.8110	21	20	n/a
Milverton	27.75	0.633	0.0141	22	18	n/a
Plynlimon flume	8.69	0.323	0	37	18	n/a
Redbourn	22.31	0.643	0.0909	22	10	False floods removed
Sprint Mill	34.8	0.453	0	45	17	n/a
Toft Newton	29.52	0.625	0.0044	40	17	Long time window
West Luccombe	20.38	0.539	0.0001	33	16	n/a

Methods of obtaining hydrographs

To evaluate the methods, the EMH was calculated for the catchments along with the 2-year flood generated in ReFH2 with both the recommended duration of rainfall

($D = Tp(1 + SAAR/1000)$) and the critical duration of rainfall (defined as the rainfall duration that gives rise to the largest peak flow), which was found through a ‘brute-force’ search of all possible durations. Here, Tp is the time-to-peak, and SAAR is the standard average annual rainfall (1961 to 1990) in mm. It should be noted that ReFH2, as with all previous methods, is calibrated to the recommended duration and so the critical duration should not be used in modelling studies unless there is strong evidence to support using the critical duration. Such evidence might include contradictory observed hydrograph shapes (noting the outcome of the analysis within this report), supported by the mitigation of large discrepancies between flood frequency estimates derived from ReFH2 and a combination of at-site and enhanced single-site analyses of observed data. Examples of when a local critical duration is more appropriate include studies in catchments containing reservoirs and when tidal influences are important.

The equation for estimating the recommended duration has not been revisited since the original Flood Studies Report (NERC 1975) and should be considered for future review.

Notwithstanding this, experience shows for ReFH that while the critical and recommended durations may differ within a catchment, the differences in the peak flow estimates are generally small.

For all the catchments, the default urbanisation parameters as recommended in Section 7.5 of Wallingford HydroSolutions (2015) are used: an impervious runoff factor (IRF) of 0.7, imperviousness factor (IF) of 0.3, and Tp scaling factor of 0.5, and only winter floods were considered in the ReFH2 method.

1.4 Comparison and evaluation

Visualisation of data

Figures 2 to 21 show all three hydrographs for each of the 20 catchments analysed, along with the hydrographs included in calculating the EMH, and one measure of spread: the sample standard deviation. We note that the curve is drawn for all percentage widths, but in practice widths with a very small number of events are omitted; those sections of curves deemed to be unrepresentative due to a lack of data are shown in dotted lines. See Section 1.4 for further discussion.

Hydrograph uncertainty

The two methods are subject to uncertainty which it is important to quantify before using results to make recommendations on flood risk. Both models have sampling error arising from taking a finite number of observations of an underlying process. In addition, the ReFH2 model also includes model error arising from the inability of the model to predict perfectly the true values of the model outputs. A discussion of the ReFH2 model uncertainty within small catchments can be read in Environment Agency (2017) and across all catchment scales in the supporting ReFH2 Technical Guidance (Wallingford Hydrosolutions 2016). In the rest of this section, we discuss sampling uncertainty with respect to the EMH method.

Figures 2 to 21 show the normalised hydrographs with measure of data variance for each of the 20 small catchments. Results are shown for:

- recommended ReFH2: blue line
- critical ReFH2: green line
- empirical Median (HWA): red line
- empirical (not recommended): dotted red line
- events recorded: grey dashes
- sample standard deviation: light red shading

The y-axes on each hydrograph shows the percentage of peak flow (from 0.0 to 1.0). The x-axes show the time relative to peak in hours (varying timescales).

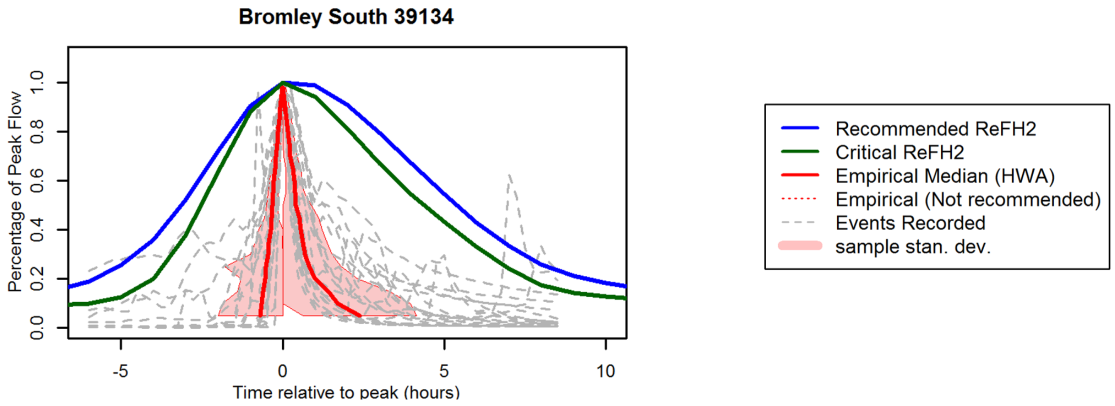


Figure 1 - Normalised hydrographs with measure of data variance (Bromley South)

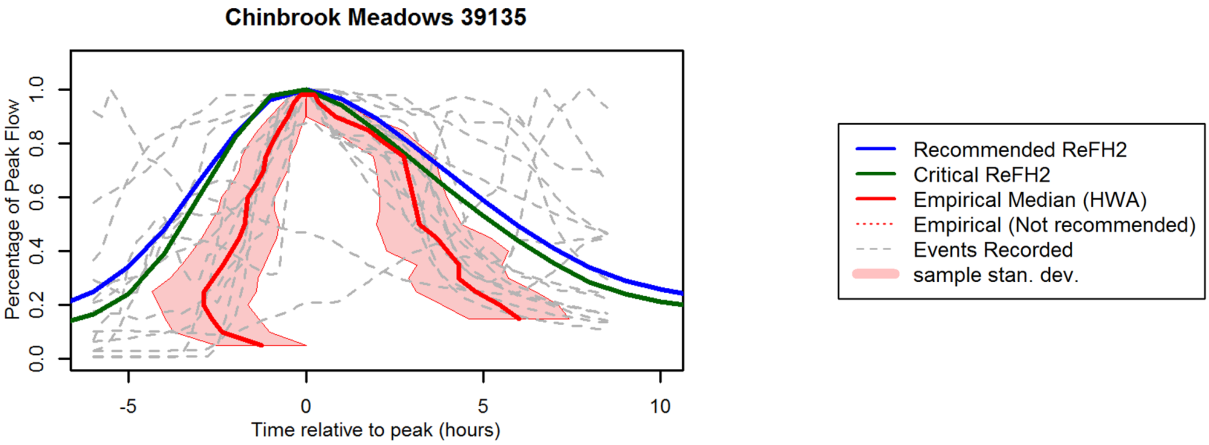


Figure 3 - Normalised hydrographs with measure of data variance (Chinbrook Meadows)

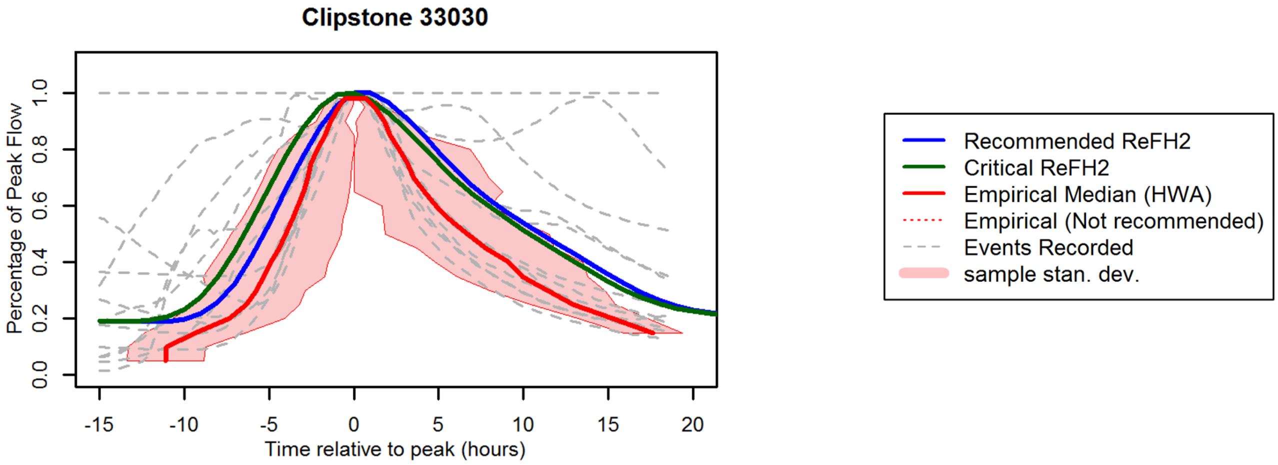


Figure 4 - Normalised hydrographs with measure of data variance (Clipstone)

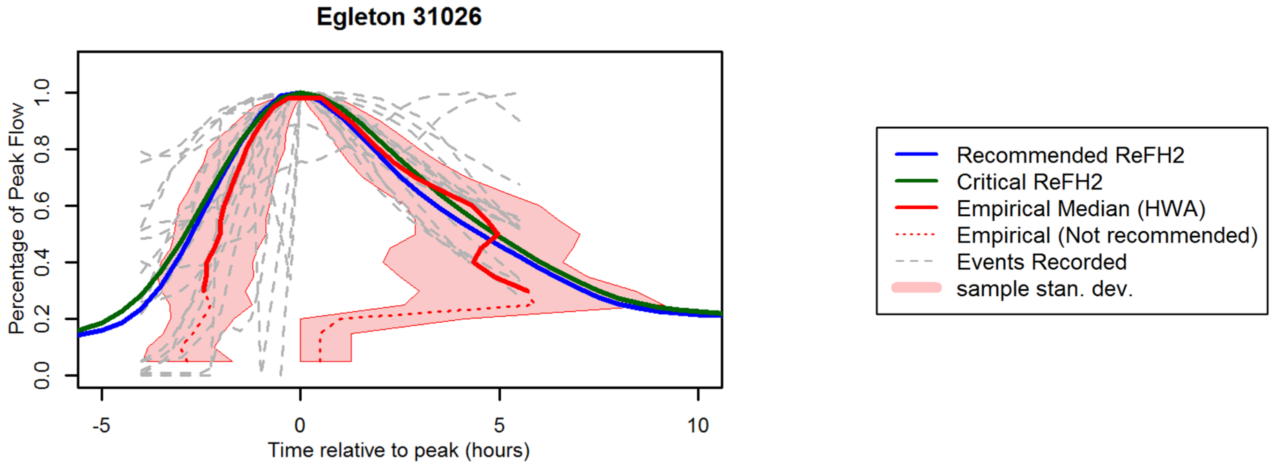


Figure 5 - Normalised hydrographs with measure of data variance (Egleton)

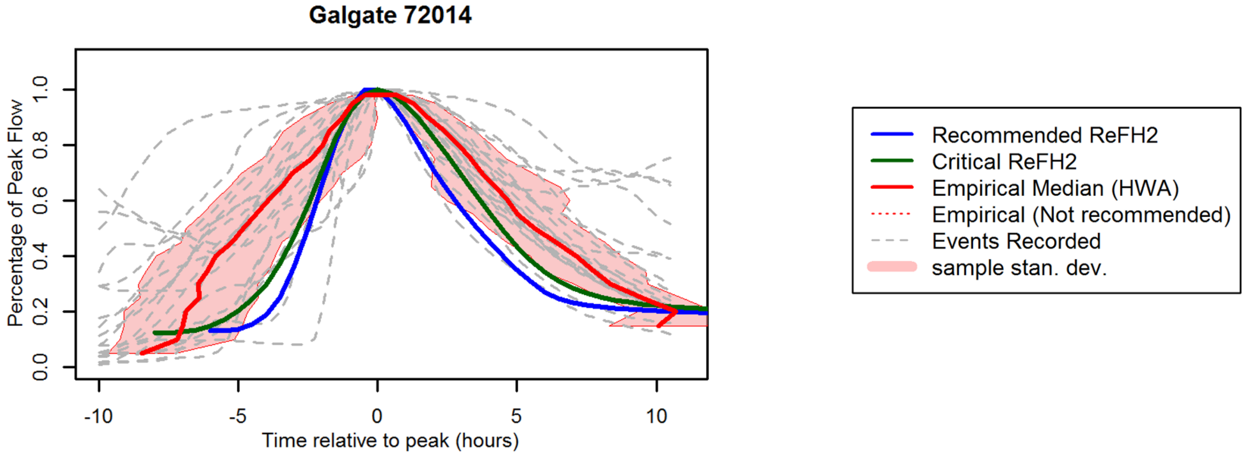


Figure 6 - Normalised hydrographs with measure of data variance (Galgate)

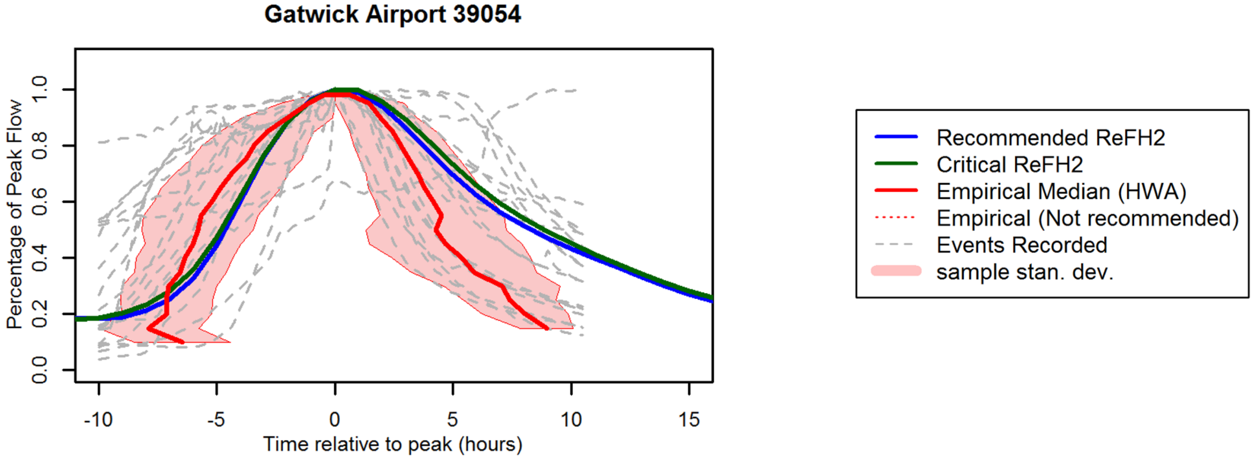


Figure 7 - Normalised hydrographs with measure of data variance (Gatwick Airport)

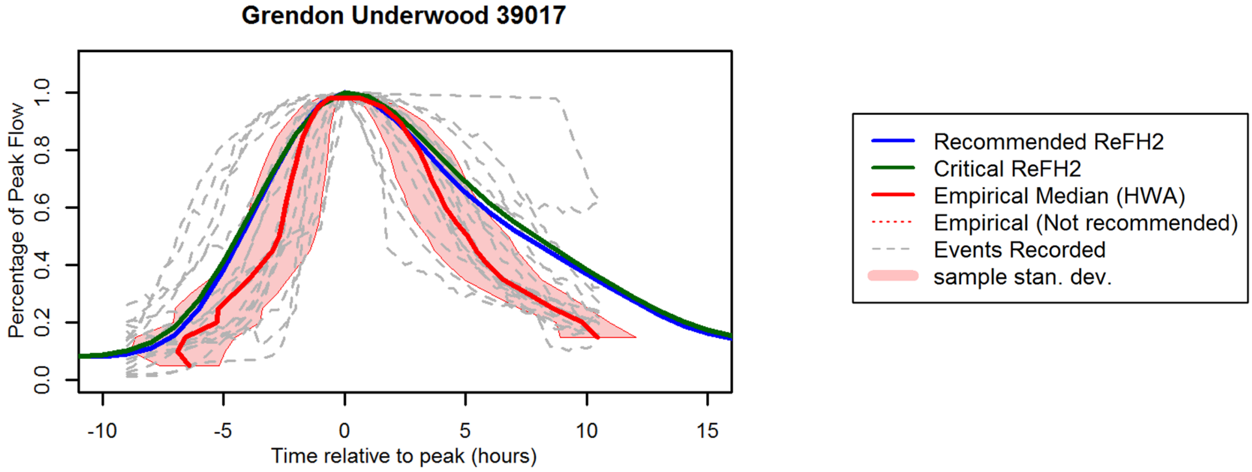


Figure 8 - Normalised hydrographs with measure of data variance (Grendon Underwood)

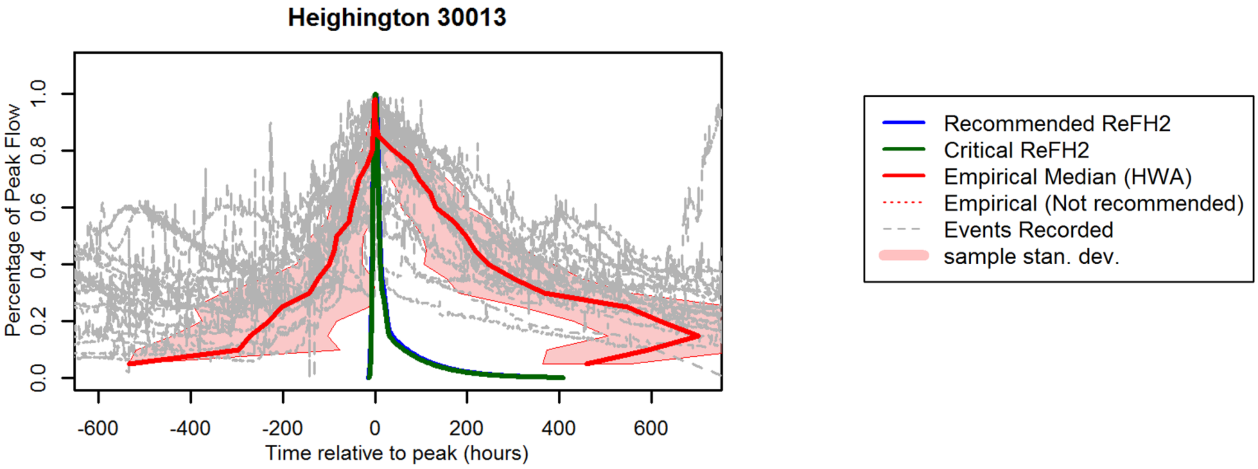


Figure 9 - Normalised hydrographs with measure of data variance (Heighington)

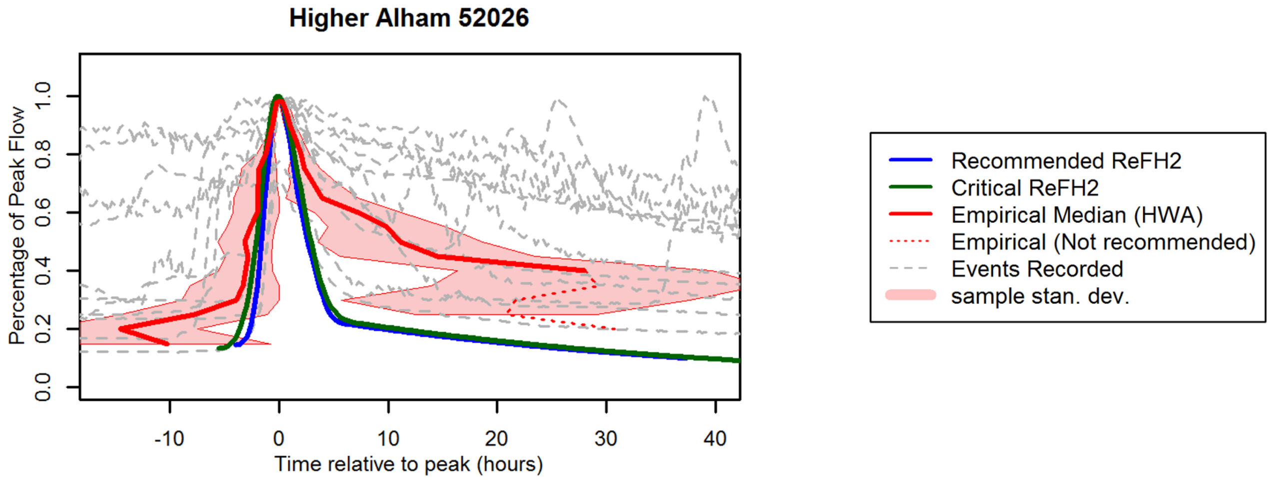


Figure 10 - Normalised hydrographs with measure of data variance (Higher Alham)

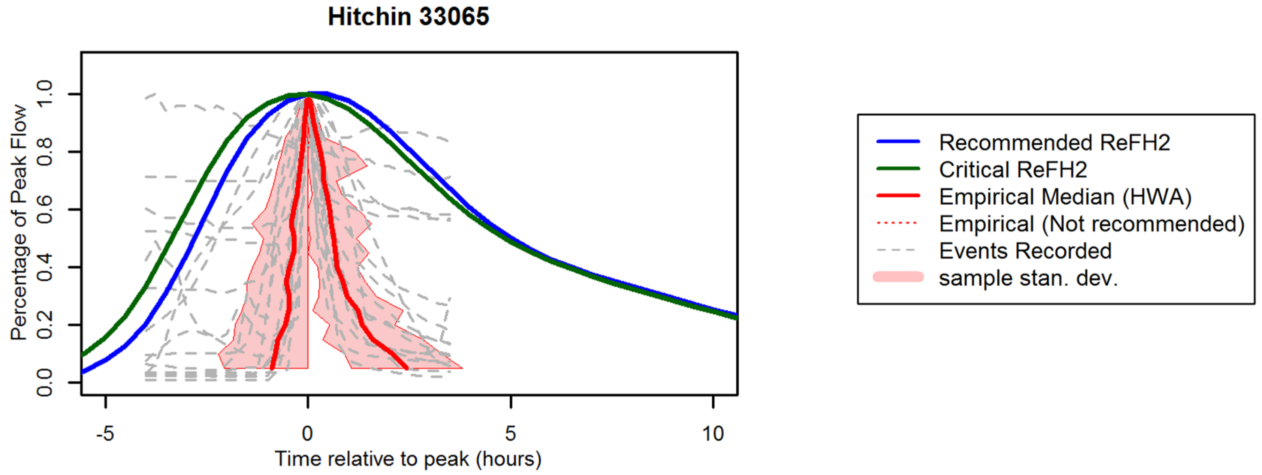


Figure 11 - Normalised hydrographs with measure of data variance (Hitchin)

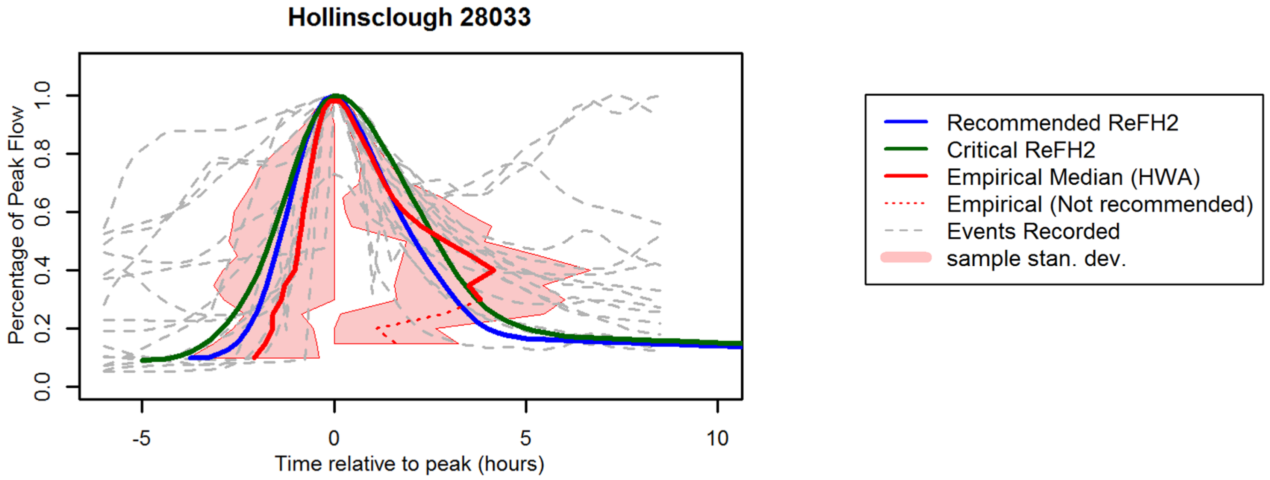


Figure 12 - Normalised hydrographs with measure of data variance (Hollinsclough)

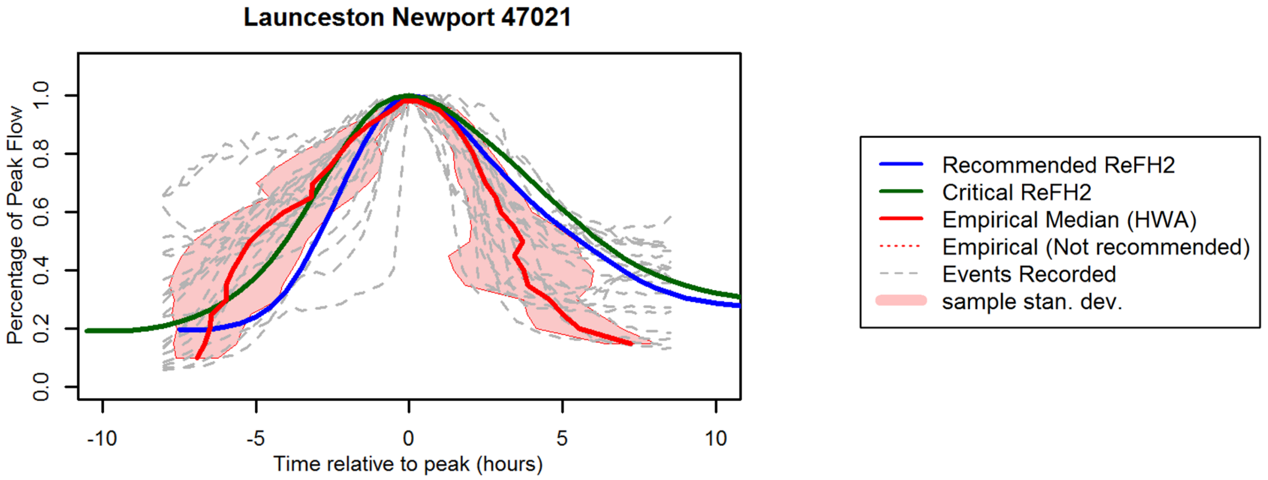


Figure 13 - Normalised hydrographs with measure of data variance (Launceston Newport)

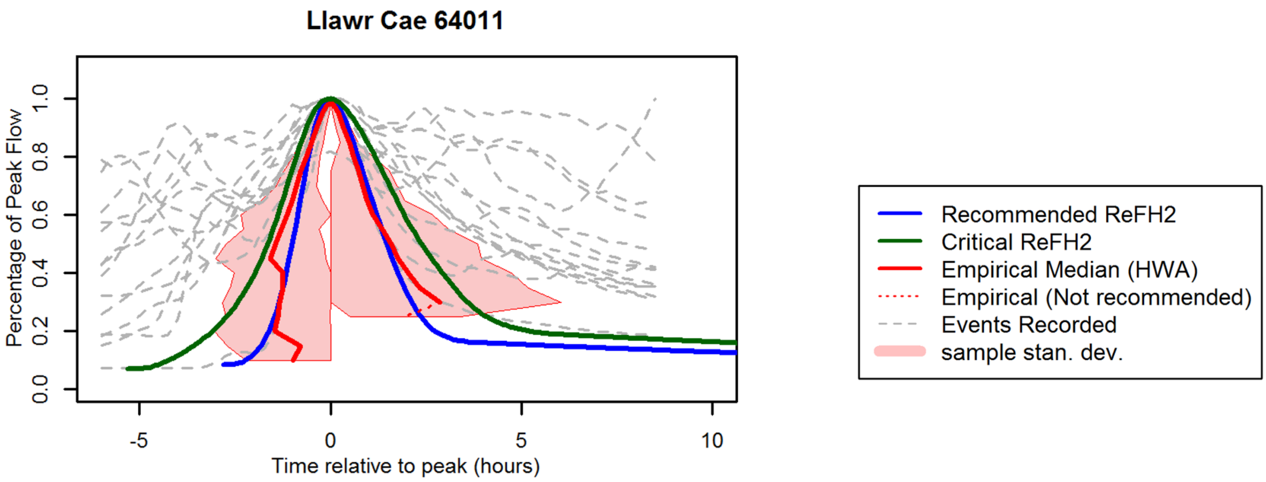


Figure 14 - Normalised hydrographs with measure of data variance (Llawr Cae)

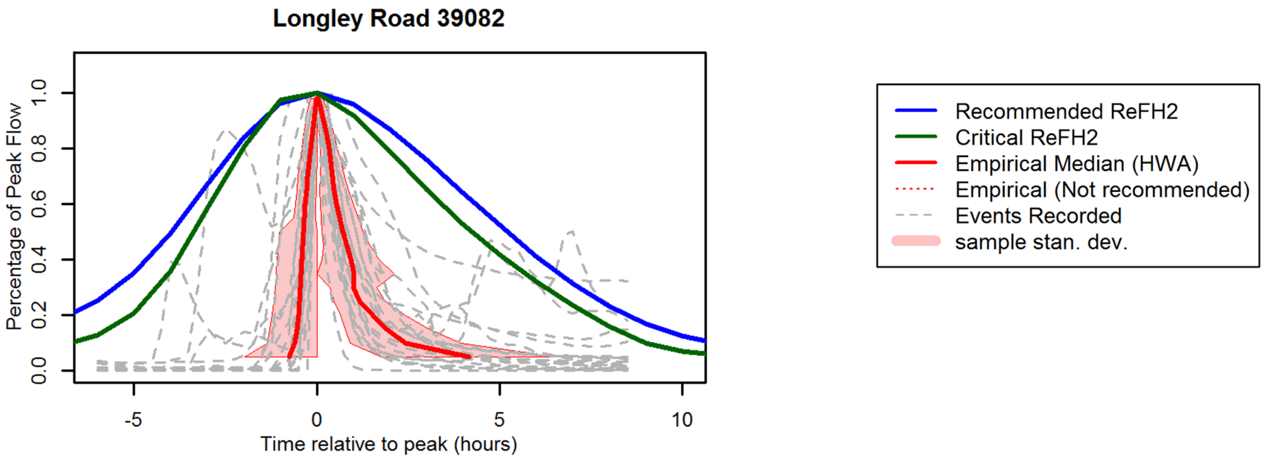


Figure 15 - Normalised hydrographs with measure of data variance (Longley Road)

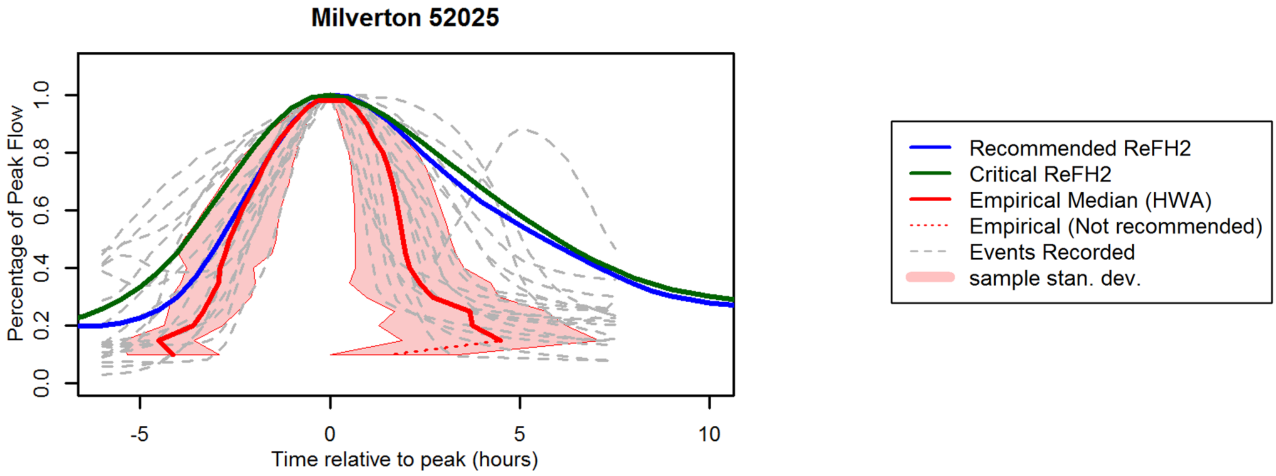


Figure 16 - Normalised hydrographs with measure of data variance (Milverton)

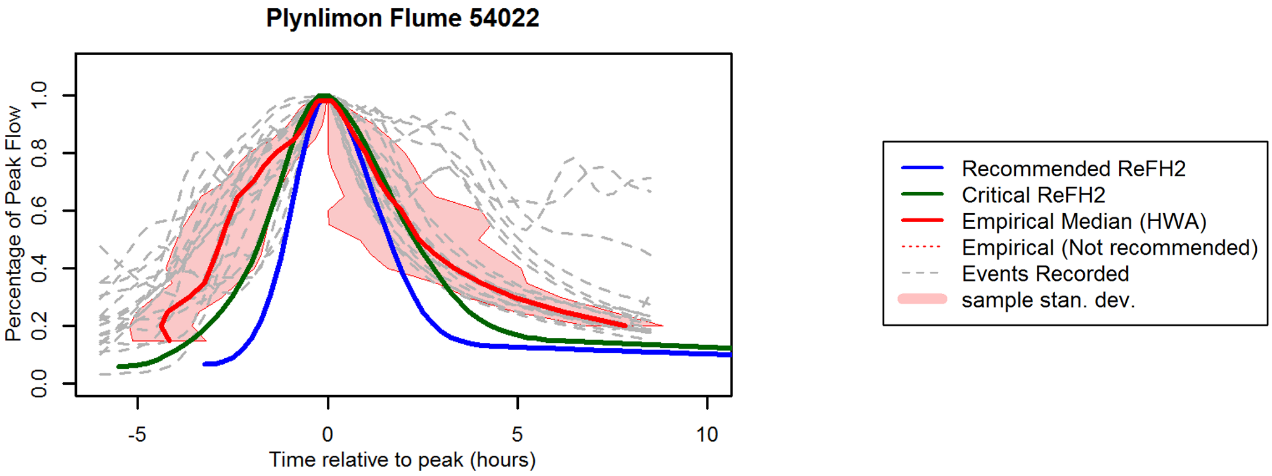


Figure 17 - Normalised hydrographs with measure of data variance (Plynlimon Flume)

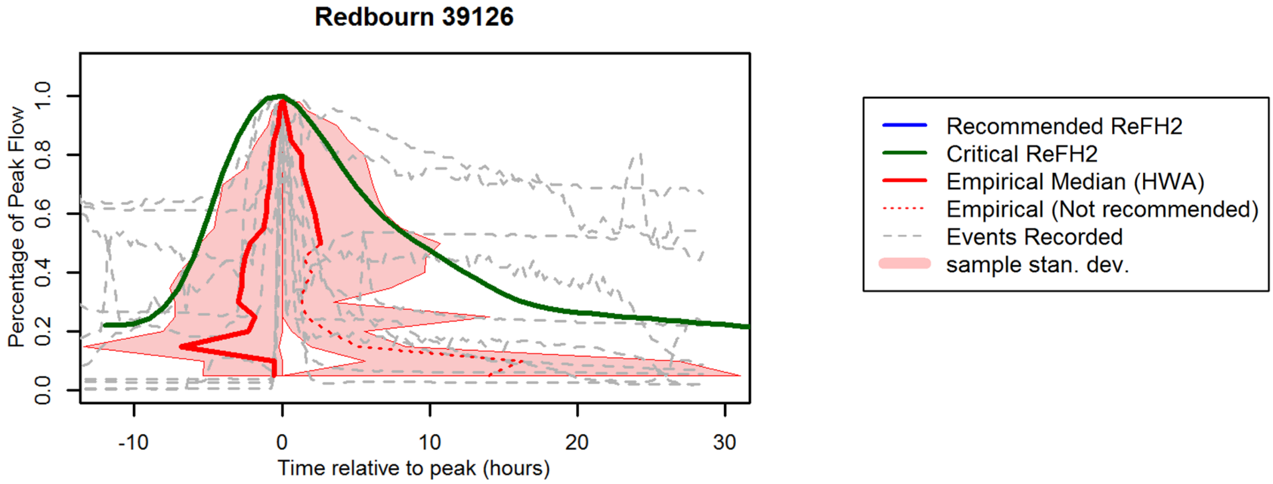


Figure 18 - Normalised hydrographs with measure of data variance (Redbourn)

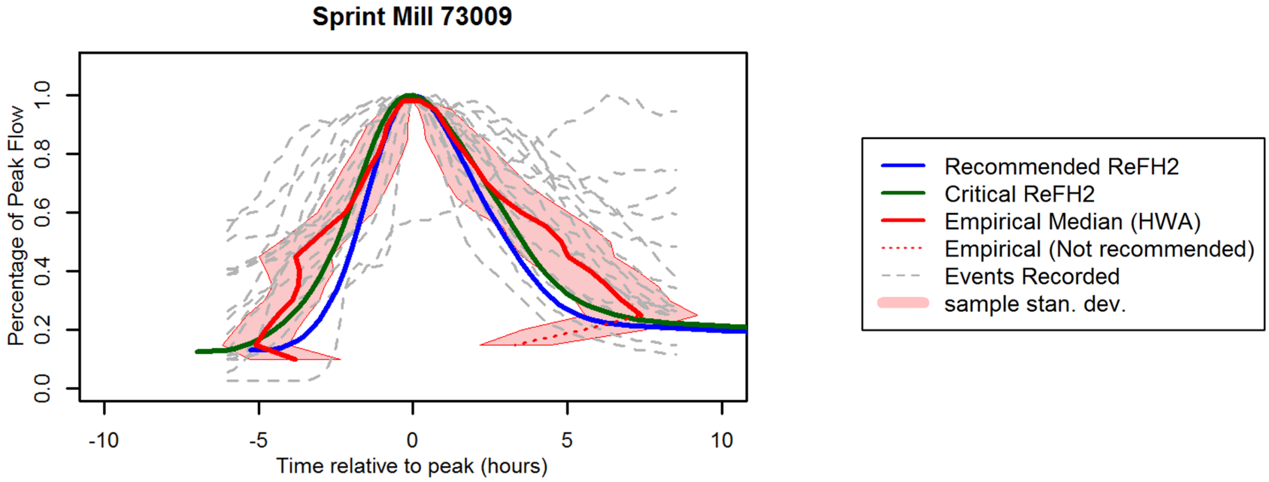


Figure 19 - Normalised hydrographs with measure of data variance (Sprint Mill)

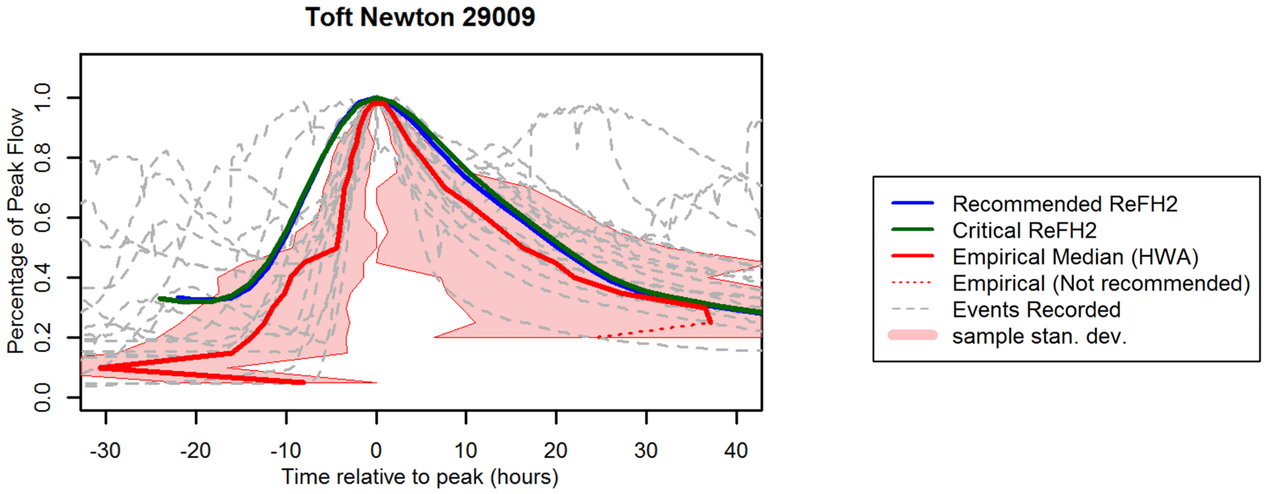


Figure 20 - Normalised hydrographs with measure of data variance (Toft Newton)

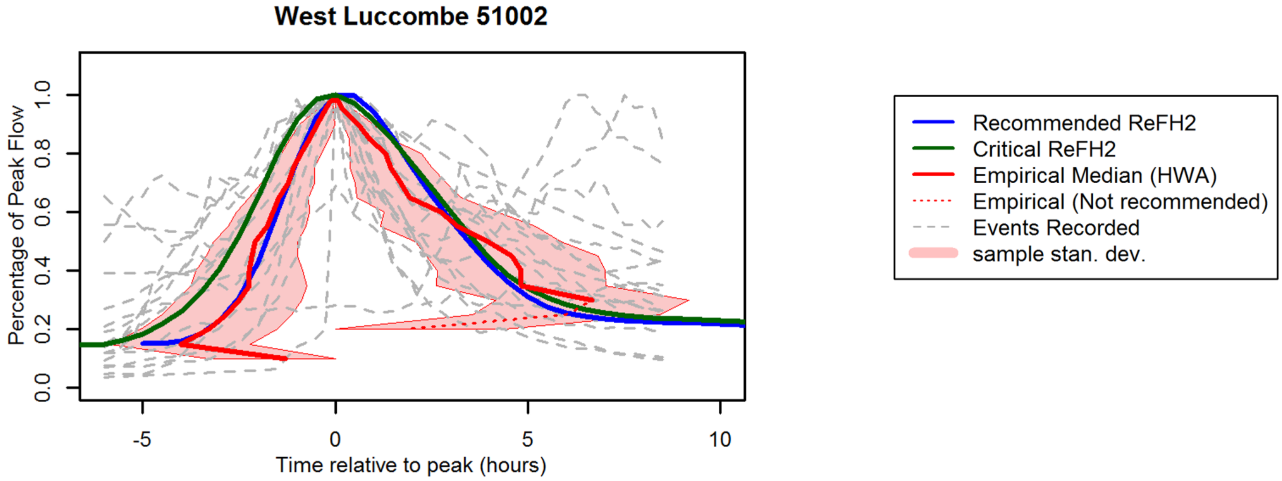


Figure 21 - Normalised hydrographs with measure of data variance (West Luccombe)

As seen in Figures 2 to 21, some of the catchments have a wide variance of event widths within the class of largest flows. One question that should be asked is whether the median hydrograph is particularly representative of such a wide variety of events. This links to the comment in Archer and others (2000) about “proportionality irrespective of peak magnitude”, and the subsequent analysis in the paper of events filtered by season and order statistic.

In order to quantify the uncertainty in the EMH method, this report will look at two metrics of the spread of the widths of the events used, the sample standard deviation, s, and the L-CV, τ, the first L-moment ratio as defined in Hosking (1990). The sample standard deviation is a measure of spread in the sense that under a single behaviour regime (up to scaling) one would expect to see a large proportion of the data lie within the interval DOE_p ± s, where DOE_p is the sample mean for percentile p of the peak flow. If DOE_p was normally distributed, one would expect approximately 65% of the data to lie within the interval DOE_p ± s. This interval is plotted as the shaded region on each of the plots in Figures 2 to 21. If the amount of data beyond the shaded region is high, it suggests that these events show different behaviour regimes between different flood events. Figure 22 shows two examples with different types of behaviour. The left panel of Figure 22 shows a single regime, and, as such, most of the observed curves lie within the shaded region. However, the right panel shows a location exhibiting two regimes (not hydrologically realistic, but illustrates the point). Even though both regimes are quite consistent, they more frequently lie outside the band due to exhibiting multiple regimes which cancel each other out if just considering mean or standard deviation.

One can see on inspection that, although some regions have a high proportion of the data within this band such as Milverton and Sprint Mill, several gauging stations, such as Llawr Cae and Redbourn, exhibit a large variance, with many events exceeding the region at several points. It should be noted that, at higher percentages of peak flow, variance should be lower, but due to inaccurate peak identification in catchments such as Chinbrook Meadows, there appears to be even more variability than would be suggested by the sample standard deviation.

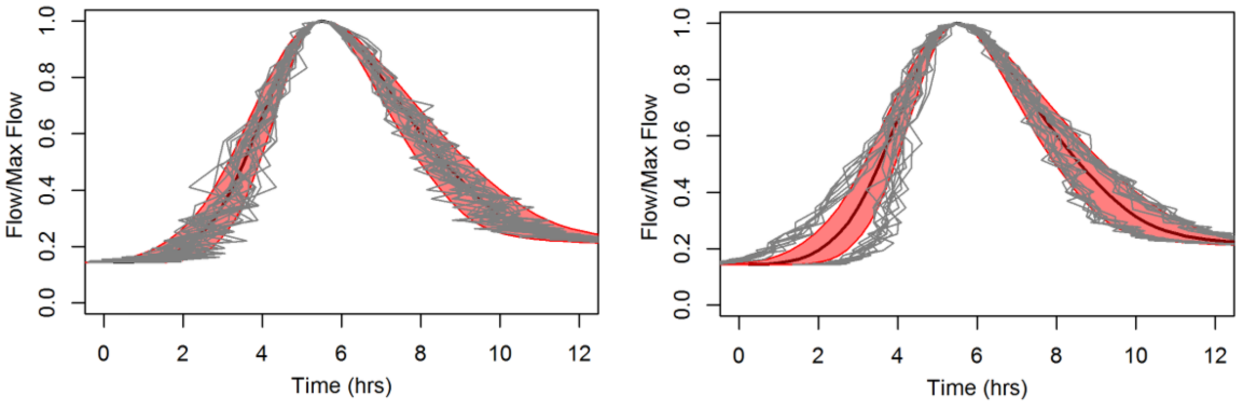


Figure 22 - Hypothetical observation sets illustrating single behaviour regime with moderate but consistent variability (left panel) and two low variance behaviour regimes often lying outside the (DOEp ± s) region (right panel)

The two hypothetical observation sets in Figure 22 show the flow/max flow on the y-axis (from 0.0 to 1.0) against the time in hours (from 0 to 12 hours) on the x-axis.

Secondly, the sample L-CV, τ, can be used to quantify this variability. According to Hosking (1990) it follows that $0 < \tau < 1$ and that constant-valued data would have $\tau = 0$. A common threshold, and one used in O'Connor and others (2014) is $\tau = 0.4$, which indicates a high amount of variability in the data. This high variability may be attributed to many things, including multiple behaviour regimes, high uncertainty in collecting data or changes in the behaviour of the channel over time.

Table 2 shows the values of the L-CV for $DOE_{50\%}$. Here, the L-CV for nearly half of the catchments exceeds 0.35 for at least one of the hydrograph limbs, and four exceed it for both. It appears that the rising limb typically has a higher L-CV, but not significantly. Although not plotted here, the L-CV was investigated for other percentages of peak flow. It was observed that L-CV was consistently larger for higher percentages of peak flow, although this may be since the L-CV is a ratio between the second L-moment and the mean, and so there are some stability issues when the values are close to zero as is the case for $DOE_{75\%}$. This can be seen in the hydrographs for stations such as Hitchin and

Redbourn (L-CV > 0.4), where the data suggests multiple types of large flood (both peaky summer and long winter floods), and the EMH only matches the sharper hydrographs. At the other end of the scale in Grendon Underwood and Sprint Mill (L-CV < 0.25), the EMH matches the more consistent shape of the selected events. Overall, L-CV is strongly affected by the amount of data and decreases as the number of events increases. Better accuracy of peak detection and isolation of event peaks also improves (reduces) L-CV.

Discrepancies between hydrographs

It can be observed that the recommended ReFH2 curve typically matches the critical curve, and even on an absolute scale (cumecs rather than percentage of peak flow) the curves only differ slightly in both peak flow and time-to-peak, the difference being less than that between the recommended and EMH curves.

The hydrographs for the two methods (ReFH2 and EMH) broadly show similar shapes for 14 out of the 20 catchments considered (70%). There are five catchments that exceed the default threshold of BFIHOST = 0.65 for defining a permeable catchment. For two of these the EMH and ReFH2 results are distinctly different. Of the six catchments for which the results are distinctly different, five have mixed geologies and BFIHOST values of more than 0.6. There is some correlation between BFIHOST and $URBEXT_{2000}$, in that all the most urban catchments are also highly permeable.

Table 2 - L-CVs for hydrograph width at 50% of peak flow

Station No.	Catchment	L-CV of 50% width (rising)	L-CV of 50% width (receding)
39134	Bromley South	0.23	0.38 (high variability)
39135	Chinbrook Meadows	0.25	0.14
33030	Clipstone	0.31	0.30
31026	Egleton	0.35 (high variability)	0.27
72014	Galgate	0.24	0.15
39054	Gatwick Airport	0.21	0.26
39017	Grendon Underwood	0.24	0.18
30013	Heighington	0.35 (high variability)	0.30
52026	Higher Alham	0.38 (high variability)	0.37 (high variability)
33065	Hitchin	0.51 (high variability)	0.36 (high variability)
28033	Hollinsclough	0.52 (high variability)	0.21
47021	Launceston Newport	0.22	0.25
64011	Llawr Cae	0.31	0.35 (high variability)
39082	Longley Road	0.49 (high variability)	0.33
52025	Milverton	0.21	0.28
54022	Plynlimon flume	0.22	0.27
39126	Redbourn	0.62 (high variability)	0.68 (high variability)
73009	Sprint Mill	0.19	0.20

Station No.	Catchment	L-CV of 50% width (rising)	L-CV of 50% width (receding)
29009	Toft Newton	0.35 (high variability)	0.37 (high variability)
51002	West Luccombe	0.30	0.27

Note: the cells showing high variability signify high levels of variability in the data (L-CV ≥ 0.35).

Catchments with low correspondence (from Table 2):

Higher Alham

Although the shape of the rising limb is consistent between the two methods, the rate of recession within the EMH estimate is much lower than that suggested by ReFH2. Inspection of the component events shows that the flow in the river is unusually sustained after the peak. The gauging station was originally developed to investigate the impact of quarrying on groundwater within this permeable, fissured limestone catchment and this observed behaviour may reflect the complex hydrology of the catchment.

Redbourn

This gauging station is gauging an ephemeral chalk catchment on the dip slope of the Chilterns with some impermeable clays within the catchment together with part of the urban development of Hemel Hempstead. Inspecting the flood hydrographs would suggest that some relate to sustained high groundwater levels within the catchment, and some relate to intense runoff from the impermeable areas. This type of dual flooding mechanism cannot be modelled directly using conceptual rainfall-runoff models such as ReFH2 or PDM together with design rainfall events, although it can be approximated through careful use of the urban modelling strategy within ReFH2. Furthermore, without carefully classifying the observed hydrographs based on the underlying flooding mechanism, the EMH results are equally difficult to approximate as a median hydrograph shape.

Longley Road

Although Longley Road is not a permeable catchment, it is small (< 5 km^2), highly urbanised ($URBEXT_{2000}$ = 0.811) and the observed runoff response is significantly peakier than ReFH2. Within the EMH hydrograph the rising limb of the hydrograph is less than one hour, almost certainly reflecting that surface water drainage rather than natural runoff is dominating the hydrograph shape in this catchment.

Bromley South

Bromley South is also a highly urbanised catchment ($URBEXT_{2000}$ = 0.487) but it is also permeable (BFIHOST = 0.685). Within the EMH hydrograph, the rising limb is also less than one hour, almost certainly reflecting that the EMH is capturing the runoff from surface water drainage rather than runoff from the underlying permeable catchment; this point is discussed further below.

Hitchin

Again, the EMH is suggesting a very flashy flood regime. This is surprising as the catchment has a BFIHOST value of 0.968 indicating a highly permeable chalk catchment. This is confirmed by inspecting the daily flow hydrograph which is a classic unconfined chalk hydrograph. It would suggest that the EMH method has selected small, short residence time events rather than the underlying groundwater trends in the flow.

Heighington

This catchment is a very permeable catchment (BFIHOST = 0.945) draining the Lincolnshire limestone. Inspecting the daily hydrograph shows that river flows are very high baseflow with an unusually suppressed within year and between year variability. This is reflected in the EMH hydrograph which has a time base of around 30 days. Although Heighington has a very high BFIHOST, the small, rare spikes within a long observation window caused a much more prominent effect, which is discussed below.

Issues with observation windows

The EMH method is also sensitive to the choice of events and window used. Some of these catchments such as Hitchin only used a very narrow window of observed data, which would lead to more biased estimates since only the very peaky curves would be those entirely within the window. Nearly a third of the events used in the calculation for the Hitchin EMH did not drop below 50% of peak flow, and so they were not included in the calculations for the lower percentages. One possible reason for this is that Hitchin demonstrates a marked seasonal variation in baseflow (with highest baseflows typically observed in the late winter/early spring). If a longer window was considered, then some of the very high baseflow events with relatively long durations may lead to slower rise and recession due to being included in calculations at lower percentiles and flatten the EMH. Since the ReFH2 model doesn’t rely on a specific window of data, such problems do not arise.

On the other hand, Heighington and Higher Alham display a much wider EMH than the ReFH2 hydrographs (although the rising limb for Alham is quite short). The events considered have a maximum peak flow of 1.2 to 1.8 cumecs although for Higher Alham they do all lie above the Higher Alham estimate of QMED. The selected hydrographs are generally multi-modal events, suggesting a combination of extended periods of generally high baseflow and relatively short-duration runoff events from the more impermeable areas within the catchment. The time base for the Heighington EMH is also very long. In the case of Heighington, the EMH is identifying long periods of elevated (presumably winter) baseflow and not the larger of the short-duration events that occur over the winter months. In contrast, the ReFH2 shape is similar to the short-duration events.

In the case of Higher Alham, the records are taken over a very short period (Nov 2008 to Dec 2009), and so this EMH may instead just be a summary of a single wet period of higher baseflow compared to the longer scale of the ReFH2 parameter calibration.

Finally, one key observation is the fact that the EMH hydrographs are not generally monotonic; there are percentage points p for which DOE_p is less than that for a lower percentage (the curve 'kinks' inward). This is a fundamental problem with the method when trying to estimate from limited data, such as Higher Alham and Redbourn, which both have fewer than 10 events each. It is also observed in locations where baseflow is a significant proportion of the total flow, such as Higher Alham. In these cases, DOE_p for low p can only be computed when data which drops to these levels is available. For small data sets, the median can be just as volatile as the mean if the data is also quite variable. This can be seen for the 25% and 20% exceedance durations of Egleton in Figure 1, where having fewer events (from five events to just one) makes a huge difference to the values obtained, when one would expect little difference between two similar percentage levels. Hydrological judgement is required to make a decision on when the HWA outputs are not used at low percentiles because the number of events drops to an unacceptably small number.

1.5 Discussion

The main issues with the EMH seems to be data-led: peak identification and flood window choices have both led to problems with analysing hydrograph shape. For small catchments where records are typically short (but are improving), this leads to volatile estimates for the EMH, where a single extra event can make a big impact at low percentages of peak flow.

The issues with non-monotonicity were also noted in Irish Flood Studies Update (O'Connor and others, 2014). In the report, three methods were used in order to avoid such problems: smoothing, omission and fitting a function. In the first case, a 3-point rolling average was applied to certain hydrographs showing small 'kinks'; this was applied repeatedly in several cases until a sufficiently smooth curve was obtained. Secondly, a mathematical function was fitted to describe the shape of the hydrograph, and this fitted curve was presented. In the more severe cases, the exceedance durations for low percentages are just removed, and only the top of the hydrograph is reported.

The discrepancies between the two models were documented even in the original study (Archer and others, 2000) and illustrated that the empirical hydrographs were flatter than the version from the parametric model in the Flood Studies Report (NERC 1975). By including seasonality and urbanisation within the ReFH2 model, it is hoped that when time series over longer periods are available that separating the data by season may improve EMH estimates by reducing variability in the underlying conditions used to compute the median widths.

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. Overall, improved peak detection and flood event window selection would lead to better, more representative EMHs for all the catchments in this report.

In conclusion, 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 within rural catchments.

A distinction between event volume and hydrograph shape is also 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.

2. Small catchments and urbanisation

2.1 Introduction

This section presents a review of the seasonality of flood events in the UK, updating work previously published within the Flood Estimation Handbook. The aim is to identify specifically when it is appropriate to use a winter storm together with the ReFH model and when a summer storm event should be used. Although the focus of this analysis is on the question of urbanisation in small catchments, a broader view has also been taken both in terms of catchment size and typology to set the outcomes of the small catchments' analysis in context.

Based upon this analysis, recommendations for when summer storms should be used have been developed using levels of urbanisation and catchment type. Building on this classification, the parameterisation of the urbanisation module within ReFH2 has been revised. Also, procedures for estimating summer design values of C_{ini} are proposed to use with the FEH13 rainfall model when summer rainfall depths are recommended in urban catchments.

Section 2.2 reviews the origins of storm seasonality in the context of design flood estimation, how this seasonality has been considered within the ReFH design package to date and the origins and applicability of the FSR summer storm profile.

The seasonality of flood events is reviewed within Section 2.3 and the proposed revisions to the ReFH2 design package for urbanised catchments are presented within Section 2.4. These revisions reflect the evidence for a seasonal signal in flood events in heavily urbanised catchments and evidence for the validity of summer storm profiles when used in these heavily urbanised catchments.

2.2 Storm seasonality within the ReFH design package

Annual maximum peak flow events in rural catchments tend to be associated with winter events because of low antecedent 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. The recorded rainfall depths associated with 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.

The design storm hyetograph model used with ReFH consists of a seasonal (winter/summer) correction factor (SCF) (Kjeldsen 2007) used together with a corresponding storm profile based on the 75% winter and 50% summer storm profiles originally developed to use within the FSR rainfall-runoff model. In use, the interpretation of the percentages is that the winter profile is more peaked than 75% of observed winter storms and the summer profile is more peaked than 50% of observed summer events. Historically, a winter storm is therefore estimated using the appropriate winter seasonal correction factor (SCF) which is a function of duration and SAAR. This SCF is then applied to the estimated design rainfall depth for the required design duration and frequency of event being modelled. The scaled rainfall depth is then distributed over the design duration using the 75% storm profile. A summer event is estimated using the same approach but using the summer equivalent SCF and 50% storm profile. The 50% storm profile is much more peaked than the winter storm profile, giving a much higher peak rainfall depth for a given total rainfall depth. For a given duration, the summer SCF approaches unity in very dry catchments and the winter SCF approaches unity in very wet catchments. The point of intersection is influenced by the duration of the storm being considered.

Using the 50% storm profile within urban catchments was originally introduced within FSR Supplementary Report No. 5 (Institute of Hydrology, 1979). Part of the rationale for introducing this was for consistency with sewer design methods at the time. The method was tested in 11 urban catchments without invoking the FSR increase in rarity of design rainfall to yield a fluvial peak flow estimate of a given rarity. This analysis identified that the increased peakedness offset the use of equal return periods for rainfall and flow design events and resulted in slight increases in peak flow estimates (generally <5%).

The FSR storm profiles have long been the subject of critical review. In general, the profiles have been criticised for being too simple, especially due to the imposed symmetry as well as for the profiles being too peaked (Faulkner, 1999). The uni-modal profiles are particularly open to criticism for very long duration events which would, in reality, be comprised of a series of rainfall events. In this report, and in the context of ReFH2 and the use of the FEH13 rainfall model, the appropriateness of the 50% and 75% storm profiles has been reviewed.

For the purposes of applying ReFH, predominantly rural catchments have historically been defined as those in which $URBEXT_{2000}$ is less than or equal to 0.15 and urbanised catchments are catchments with $URBEXT_{2000}$ values greater than this threshold. Using this definition, a summer storm was recommended for use in urbanised catchments and winter storms for rural catchments within the development of the original ReFH model (now known as ReFH1). ReFH1 provided design initial condition estimates for antecedent soil moisture content (C_{ini}) and baseflow (BF_0). A summer design C_{ini} model was derived for the small number of urban catchments within the ReFH1 data set by identifying the C_{ini} required to generate a peak flow equivalent to the estimate of the 5-year return period event for each catchment derived from analysis of the annual maximum data. The resultant calibrated C_{ini} values were then generalised to develop a design equation.

The main point is that this was assuming a summer storm profile. The peakier summer storm profile in turn results in a lower optimal C_{ini} value than the corresponding winter profile. From a hydrological perspective, this is an attractive outcome; summer soil moisture deficits are generally higher than winter deficits. However, this reasoning is undermined by the observation that the individual event C_{ini} values identified in the ReFH calibration catchments (used to parameterise the model for developing the design package) generally show no seasonal dependency. This outcome is because the within-season variation in the antecedent C_{ini} values is generally much greater than the relative differences between average winter and average summer antecedent soil moisture conditions. Considering hydrological processes, it would be reasonable to suggest that persistent seasonal patterns in soil moisture deficits will be more prevalent in drier permeable catchments.

In contrast with C_{ini}, there is a definite seasonal variation in the event values of BF_0. Within ReFH2, the current design estimate of C_{ini} does not depend on seasonality whereas the design estimates of BF_0 are seasonal. This is discussed within Appendix 3 of the ReFH2 guidance (Wallingford HydroSolutions, 2016)

2.3 A review of flood seasonality and dependencies on level of urbanisation

Objectives

The seasonality of flooding in urban catchments has been reviewed across a range of catchment scales, although it is accepted that the most heavily urbanised catchments tend to be small catchments. Bayliss and Jones (1993) tested two different flood seasonality measures for 857 catchments in the UK. This study showed that catchments dominated by summer floods tended to be catchments with catchment areas less than 150 km^2 but that the dominant influence was the level of urbanisation. The Flood Estimation Handbook later reported that floods in rural catchments tend to be winter floods, while in urban catchments floods tend to be all year or summer floods with a much wider range of flood seasonality.

The choice of a winter or summer storm profile within the ReFH methodology has a profound impact on the magnitude of the peak flow estimate for a given set of initial conditions. The original ReFH research identified and recommended separate initial conditions for summer storms, although this was essentially an analysis of urban catchments. The drier antecedent conditions required in these catchments might reflect the impact of summer soil moisture deficits, but equally it could be the outcome of a requirement for lower C_{ini} values to compensate for the peakiness of the summer storm profiles.

On the other hand, in developing ReFH2 there was little evidence to suggest that summer storms should be considered apart from in the most urbanised catchments. A question is whether this conclusion was masked by scale effects across the wide range of catchments used in characterising initial soil moisture conditions and, furthermore, whether the relatively small number of small, heavily urbanised catchments in the data set meant it was difficult to identify the influence of urbanisation on seasonality.

This section seeks to review the evidence for using summer storm conditions in urban catchments by looking again at the influence of catchment scale, natural typology (climate and permeability) and urbanisation on the seasonality of flood regimes. The analysis has considered both the current small catchment data and the combined small catchments and full NRFA peak flows data set. Based on this analysis, recommendations are made as to when summer storms should be used within the ReFH2 methods in urban catchments and at what level of urbanisation.

Estimating flood seasonality

Flood seasonality refers to the timing of flood events within a year. Timing and regularity of hydro-meteorological variables are usually described in terms of directional or circular statistics (Fisher 1993). The dates of floods are represented on a circle of unit radius by converting the Julian day (DOY) in which the annual maximum occurred to an angular value according to Equation 1:

Equation 1 – Converting day-of-year to angular value for circular plotting

$$\theta_i = \left(DOY_{AMAX_i} - 0.5\right) \cdot \frac{2\pi}{LENYR}$$

In Equation 1, LENYR is the number of days in the year (365, or 366 in leap years) and the correction 0.5 adjusts θ to the middle of the day.

The annual maximum dates for a given station are placed on a unit radius circle, with the angle representing the date, as illustrated in Figure 23. The centroid of these points, the red point in Figure 23, is used to summarise the seasonal behaviour of the station providing:

- the mean date of the year in which the annual maxima occur, which is summarised by $\bar{\theta}$
- the concentration of the seasonal distribution, which is summarised by the length $\bar{r}$

The closer the value of $\bar{r}$ is to 1, the more floods occur around the same date, that is, the stronger the seasonal signal.

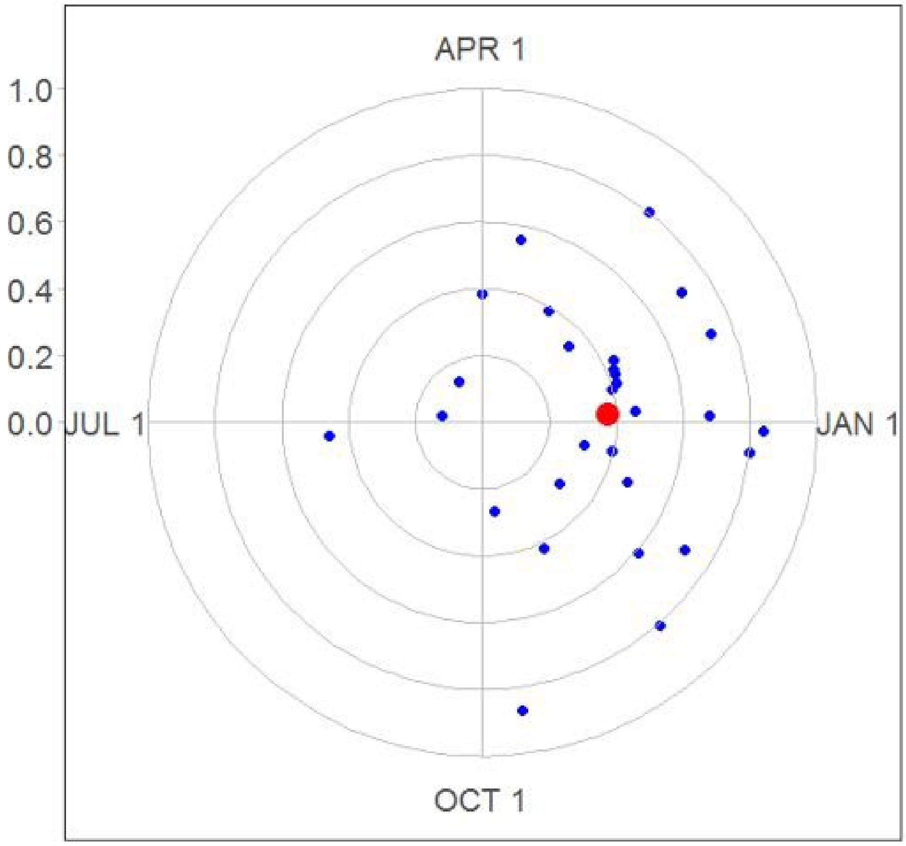


Figure 23 - Annual maximum dates (in blue) represented on a circle of unit radius (centre of mass shown in red)

The centroid can be represented both in polar coordinates ($\bar{\theta}$and $\bar{r}$) or by Cartesian coordinates XFLOOD and YFLOOD given by Equation 2 and Equation 3:

Equation 2: XFLOOD Cartesian coordinate

$$XFLOOD = \frac{1}{n}\sum_{i=1}^{n} cos\ \theta_i$$

Equation 3: YFLOOD Cartesian coordinate

$$YFLOOD = \frac{1}{n}\sum_{i=1}^{n} sin\ \theta_i$$

The dates of flood can be also weighted by their magnitude. In the latter case, XFLOOD and YFLOOD are given by Equation 4 and Equation 5:

Equation 4 – Dates of flood weighted by their magnitude (XFLOOD)

$$\boldsymbol{XFLOOD = \frac{1}{n}\sum_{i=1}^{n} R_i . \cos\ \theta_i}$$

Equation 5 – Dates of flood weighted by their magnitude (YFLOOD)

$$YFLOOD = \frac{1}{n}\sum_{i=1}^{n} R_i . \sin\ \theta_i$$

In Equations 4 and 5, $R_i = AMAX_i\ /\ max(AMAX_i)$ is the weight assigned to each AMAX value.

Results and discussion

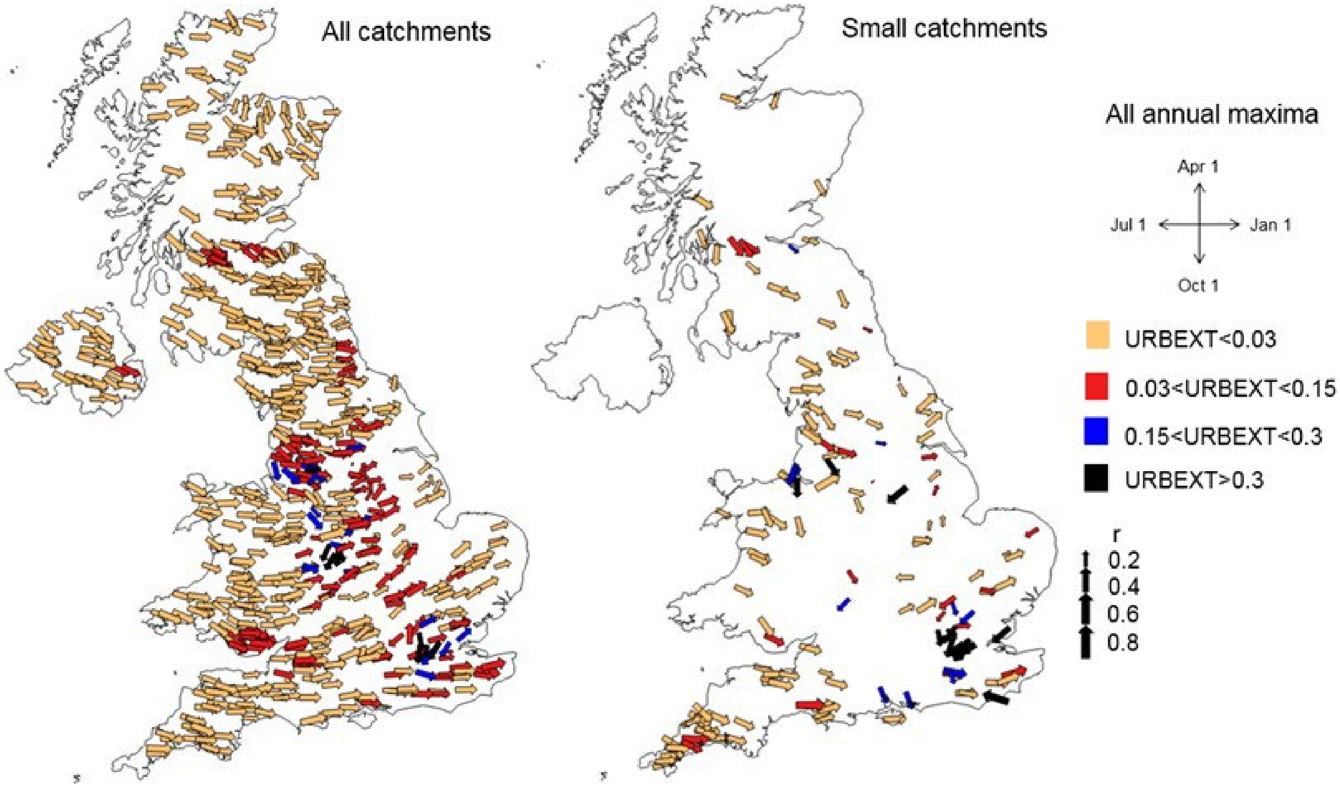


Figure 24 - Flood seasonality maps for all the UK catchments (left-hand side) and for the small catchments (right-hand side) categorised by urbanisation influence based on all the flood annual maxima

Figure 24 shows a map of UK flood seasonality based on the annual maxima provided by WINFAP-FEH v4.1 for the small catchment data set and additionally, for context, all catchments in the NRFA peak flows database.

As discussed, the direction and the size of each arrow represent the mean flood date and the concentration of the seasonal distribution. In Figure 24 the catchments are categorised by the degree of urbanisation (as represented by the $URBEXT_{2000}$ catchment descriptor).

Considering 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, apart from 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 convective storms - convective storms have a limited spatial extent but can be a source of extreme floods in small rural catchments

The balance in the previous bullet 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 shown:

- very heavily urbanised catchments ($URBEXT_{2000} > 0.3$) tend to be small catchments, as would be expected
- very heavily urbanised catchments ($URBEXT_{2000} > 0.3$) tend to have 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. These results are presented in Figure 25. This confirms the general patterns observed for all maxima but with much more noise in the patterns. This outcome should be interpreted with care as the seasonality is being computed from three values (therefore strength of the signal is not relevant). 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 still that in rural catchments winter storms tend to dominate and in very heavily urbanised catchments summer events tend to dominate.

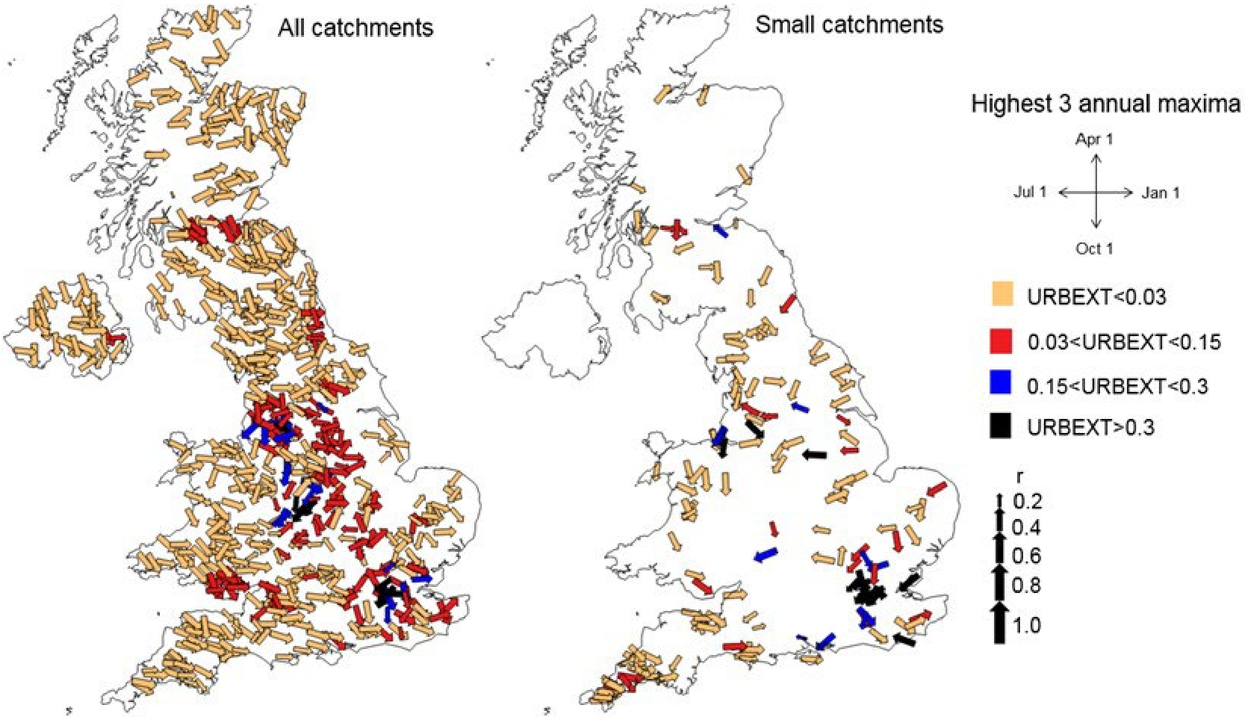


Figure 25 - Flood seasonality maps for all the UK catchments (left-hand side) and for the small catchments (right-hand side) categorised by urbanisation influence based on the highest three flood annual maxima

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) have been categorised by catchment type according to climate (SAAR), permeability (BFIHOST) and scale (AREA). For each typology index, catchments have been classified by the extent of urbanisation (see Tables 3 to 5). Within each urbanisation class catchments are differentiated by seasonality, summarised as the percentage of summer and winter events respectively. This analysis does not differentiate on the strength of the seasonal signal, just that it is present. Summer is defined as April to the end of September and winter as October to the end of March. The number of catchments with winter and summer storms are presented for each rainfall-urbanisation class and are also summarised as the percentage of storms that occur within the summer period.

The threshold of 800 mm for SAAR was selected based on water resource hydrology research (Holmes and others, 2002) that suggests in a UK context, evaporation-limiting summer soil moisture deficits occur in most years for catchments with SAAR less than 800 mm. The BFIHOST threshold of 0.65 reflects the generally accepted threshold for defining permeable catchments from a flood's perspective, and the AREA threshold of 40 km^2 represents the selection criterion for the current project.

Table 3 - Relationships between the seasonality of annual maxima, levels of urbanisation and average annual rainfall (number/proportion of catchments in each class)

Range of $URBEXT_{2000}$	Number of catchments with SAAR ≤ 800 mm (summer)	Number of catchments with SAAR ≤ 800 mm (winter)	Number of catchments with SAAR > 800 mm (summer)	Number of catchments with SAAR > 800 mm (winter)	% summer ≤ 800 mm	% summer > 800 mm
$URBEXT_{2000}$ < 0.03	7	132	17	435	5.04	3.76
$URBEXT_{2000}$ ≥ 0.03 to 0.15	9	74	2	68	10.84	2.86
$URBEXT_{2000}$ ≥ 0.15 to 0.30	2	16	1	10	11.11	9.09
$URBEXT_{2000}$ ≥ 0.30	10	7	2	3	58.82	40.00
Total no. of catchments	28	229	22	516	n/a	n/a

Table 4 - Relationships between the seasonality of annual maxima, levels of urbanisation and BFIHOST (number/proportion of catchments in each class)

Range of $URBEXT_{2000}$	Number of catchments with BFIHOST < 0.65 (summer)	Number of catchments with BFIHOST < 0.65 (winter)	Number of catchments with BFIHOST ≥ 0.65 (summer)	Number of catchments with BFIHOST ≥ 0.65 (winter)	% summer < 0.65	% summer ≥ 0.65
$URBEXT_{2000}$ < 0.03	22	485	2	82	4.34	2.38
$URBEXT_{2000}$ ≥ 0.03 to 0.15	6	116	5	26	4.92	16.13
$URBEXT_{2000}$ ≥ 0.15 to 0.30	1	23	2	3	4.17	40.00
$URBEXT_{2000}$ ≥ 0.30	10	8	2	2	55.56	50.00
Total no. of catchments	39	632	11	113	n/a	n/a

Table 5 - Relationships between the seasonality of annual maxima, levels of urbanisation and catchment area (number/proportion of catchments in each class

Range of URBEXT$_{2000}$	Number of catchments with AREA ≤ 40 km^2 (summer)	Number of catchments with AREA ≤ 40 km^2 (winter)	Number of catchments with AREA > 40 km^2 (summer)	Number of catchments with AREA > 40 km^2 (winter)	% summer ≤ 40 km^2	% summer > 40 km^2
URBEXT$_{2000}$ < 0.03	13	104	11	463	11.11	2.32
URBEXT$_{2000}$ ≥ 0.03 to 0.15	4	14	7	128	22.22	5.19
URBEXT$_{2000}$ ≥ 0.15 to 0.30	0	11	3	15	0.00	16.67
URBEXT$_{2000}$ ≥ 0.30	5	7	7	3	41.67	70.00
Total no. of catchments	22	136	28	609	n/a	n/a

Based on the observations in Tables 3 to 5, 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 catchment (URBEXT$_{2000}$ < 0.15) for all catchment types
- summer storms dominate the flood regime of catchments in the ‘very heavily urbanised’ class (URBEXT$_{2000}$ ≥ 0.30)
- within the 0.15 ≤ URBEXT$_{2000}$ < 0.30 interval, if the SAAR value is less than 800 mm and the catchment is permeable (BFIHOST > 0.65), then there is some evidence to suggest that summer floods may dominate, otherwise the dominant flood season is still winter

The lack of a dependency on scale is surprising, although the threshold of 40 km^2 may influence the outcome, compared with the threshold of 150 km^2 used by Bayliss and Jones (1993).

The scale effect can be conceptualised as the idea that extreme summer storms tend to be convective in nature, therefore limited in spatial extent and therefore more likely to cause large floods in smaller catchments. This is reasonable but the lack of evidence in the data set may reflect that the catchments are small and the sampling of events resulting from coincident thunderstorms may just be low. That is, the probability that a large convective storm with a limited footprint coincides with a small catchment that happens to be gauged is low, particularly when compared with the prevalence of winter flooding events associated with frontal precipitation over large spatial scales.

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

- if $URBEXT_{2000}$ is ≥ 0.30, summer storms should be used
- if $0.15 \leq URBEXT_{2000} < 0.30$ and BFIHOST is ≥ 0.65 and SAAR is < 800 mm, summer storms should be used
- in all other cases, winter storms should be used

2.4 Revision of the parameterisation of the ReFH2 urbanisation model

The previous section demonstrated that catchment scale is unrelated to event seasonality, although as small catchments are more likely to have higher levels of urbanisation than larger catchments, they are more likely to be classified as sensitive to summer events. This section is relevant to both small and larger catchments and the revision of the urbanisation model has considered whether:

- a summer design C_{ini} is warranted when the summer SCF is applied to the design rainfall depth and whether it is sensitive to the choice of storm profile used (together with the summer initial baseflow)
- it is appropriate to apply SCFs and distinct winter and summer storm profiles as represented by the FSR 75% winter and 50% summer profiles
- the current default parameters for the ReFH2 urbanisation module should be revised in the context of the outcomes of the above analysis based on a recommendation to use summer conditions in heavily urbanised catchments and above, based on the rules for defining when this is the case within the previous section

The basic approach to this evaluation has been to evaluate the sensitivity of model estimation bias in urbanised catchments to the parameterisation of the ReFH2 urbanisation module under the following scenarios:

1. winter SCF, C_{ini} and 75% winter storm profile for all urban catchments

2. summer SCF, C_{ini} and 50% summer storm profile for catchments with a summer seasonality and winter scenario for other catchments
3. summer SCF and C_{ini} but under a 75% winter storm profile for catchments with a summer seasonality and winter scenario for other catchments

Scenario 1 is a control scenario and scenarios 2 and 3 differentiate the value of using the historical full summer design storm for catchments with a summer seasonality (2), and the value of retaining a standard 75% winter storm profile, but differentiating between summer and winter conditions through the value of C_{ini} and the choice of SCF. The FEH13 rainfall model has been used for all scenarios, and the winter BF_0 is used under scenario 1, with the summer BF_0 used for scenarios 2 and 3.

The ReFH2 method allows the urban component of the hydrograph to be modelled explicitly and is summarised in Section 2.4. The evaluation of whether a summer design C_{ini} is appropriate is discussed in Section 2.4 for scenarios 2 and 3. The re-evaluation of the default parameterisation of the urbanisation model in both small and all catchments is presented in Section 2.4 for all scenarios. Finally, recommendations are made for using ReFH2 within urban catchments.

The ReFH2 urbanisation model

The ReFH2 method allows the urban component of the hydrograph to be modelled explicitly within the main model components: the loss model, routing model and baseflow model. The approach is described in more detail by Kjeldsen and others (2013). The conceptual model assumes that the urban area within a catchment consists of both impervious and pervious (rural) surfaces. The impervious surfaces and a portion of the rural surfaces within the urban fraction may be positively drained and therefore the time-to-peak will be shorter than for the equivalent rural catchment.

Within ReFH2 the catchment is partitioned into the rural and urban parts of the catchment. The rural part of the catchment is modelled using the as-rural design package. The urban part is modelled using a mixed impervious surface/rural model which is described in the following sections.

Loss model

The percentage runoff is considered as a weighted sum of the contributions from the rural and urban parts of the catchment. The percentage runoff is therefore estimated separately for each of the main two land cover classes urban (which include urban, suburban and inland bare ground) and rural (non-urban) as shown in Equation 6:

Equation 6 – Estimating percentage runoff

$$PR = (1 - 1.567\ URBEXT_{2000})PR^{(rural)} + 1.567\ URBEXT_{2000}PR^{(urban)}$$

In Equation 6, $PR^{(rural)}$ is the percentage runoff from the rural part of the catchment estimated using the original loss model and $PR^{(urban)}$ is the percentage runoff from the urban area as defined by $URBAN_{50k}$ (as mapped on the Ordnance Survey 1:50K Landranger map series). A fraction of the urban extent comprises impervious surfaces, the impervious fraction (IF) and a fraction of the rainfall incident on the impervious surface forms direct runoff, the impervious runoff fraction *(IRF).* The percentage runoff for the urban area $PR^{(urban)}$ consists of contributions from both impervious and pervious areas as shown in Equation 7:

Equation 7 – Percentage runoff for the urban area

$$PR^{(urban)} = IF\ PR^{(imp)} + (1 - IF)PR^{(rural)}$$

Combining these two equations yields the following (shown in Equation 8):

Equation 8 – Percentage runoff for a mixed urban/rural catchment, expressed in terms of percentage runoff from rural surfaces and from impervious surfaces

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

The maximum percentage runoff that can be generated from an impervious surface is 100% of the rainfall that falls upon the surface. This assumes that all runoff from impervious surfaces is captured by surface water drains or flows overland towards the river. The current defaults assume that only a some of the rainfall will form runoff commonly this is assumed to be around 70%. The consequence of this is that 30% of the rainfall is either retained on the impervious surfaces or percolates through cracks or runoff to adjacent ground. If it is not retained on the surface, the net effect would be to reduce the impervious surface area as this runoff or percolation would contribute to the greenfield rate. This ‘loss’ of 30% of rainfall is counter-intuitive and therefore IF might be regarded as an effective impervious fraction. If the fraction of rainfall that forms runoff from impervious surfaces is defined as the impervious runoff factor (IRF) expressed as a percentage, then this produces Equation 9 (where R is the total rainfall depth over the event):

Equation 9 – Calculation of $PR^{(imp)}$ from impervious runoff factor and event rainfall depth

$$PR^{(imp)} = IRF \times R$$

Within ReFH2, the IF and IRF values are user-defined values (as these are properties of the type of urban area) for which the current defaults are 0.3 for IF and 0.7 IRF. Within ReFH2, Equation 8 is multiplied through by R/100 to convert the calculation to units of depth and applied to each time step within the event. The ReFH rural direct runoff is the basis of the calculation of rural runoff and the impervious runoff calculated from the product of IRF and the rainfall depth within the time step.

Routing and baseflow model

For applying to the catchment, the impact of urbanisation on reducing response time has been determined by introducing separate unit hydrographs for routing the excess rainfall generated from the rural and urban areas (comprising both impervious and pervious parts of the catchments). The Tp, time-to-peak parameter value, for the urban area is expressed as a ratio of the (larger) Tp for the rural area to the urban Tp. The same basic dimensionless shape of the unit hydrograph is retained as for the rural area. A default value of 0.5 is used for the Tp ratio, although again this can be refined by the user.

Within the ReFH2 model there is a direct link between the routed direct runoff and recharge within the baseflow model. The baseflow routing is modified for urban areas such that the recharge is related to only the direct runoff from the rural area. Without this modification, an increase in routed direct runoff from the urban area would automatically result in an increase in baseflow. This would be hydrologically counter-intuitive.

The requirement for summer C_{ini} values within permeable catchments

Currently within ReFH2 it is recommended that winter storms are used in all but the most heavily urbanised catchments using the 75% winter profile. The design estimates of C_{ini} are a function of BFIHOST only when the FEH13 rainfall model is used, and these are optimised under the assumption of a winter storm profile.

These recommendations were developed outside the current project as follows. The design C_{ini} value required for a catchment to estimate the QMED event when ReFH2 is used together with the design package model parameters and the RMED design storm for the recommended duration was identified. Rural catchments ($URBEXT_{2000} \leq 0.03$), with negligible influence from storage ($FARL \geq 0.9$), of suitable length (greater than 13 years of record) and suitable for estimating QMED from within the NRFA peak flows data set (version 3.3.4) were used for this process. A model relating these values to catchment descriptors was then developed. Following this approach, a single model was identified relating C_{ini} to BFIHOST for all catchments, irrespective of permeability. This is documented in Appendix 3 of the ReFH2 Technical Guide (Wallingford HydroSolutions, 2016).

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. Two scenarios were evaluated, a summer SCF and 50% summer storm profile (to inform scenario 2: summer, 50% profile) and a summer SCF used with the 75% winter storm profile (to inform scenario 3: summer, 75% profile). A summer BF_0 was used for both scenarios. The catchment data set consisted of 590 catchments comprising 43 catchments that are uniquely in the small catchments data set, 71 that lie in both the NRFA peak flows and small catchments data set and 476 catchments from the NRFA peak flows catchment data set only.

The C_{ini} values (expressed as a proportion of C_{max}) required to reconcile the modelled estimates of QMED with the data-based estimates of QMED under each scenario are plotted in Figure 26 as a function of BFIHOST. The ReFH2-FEH13 winter C_{ini} model is included for reference.

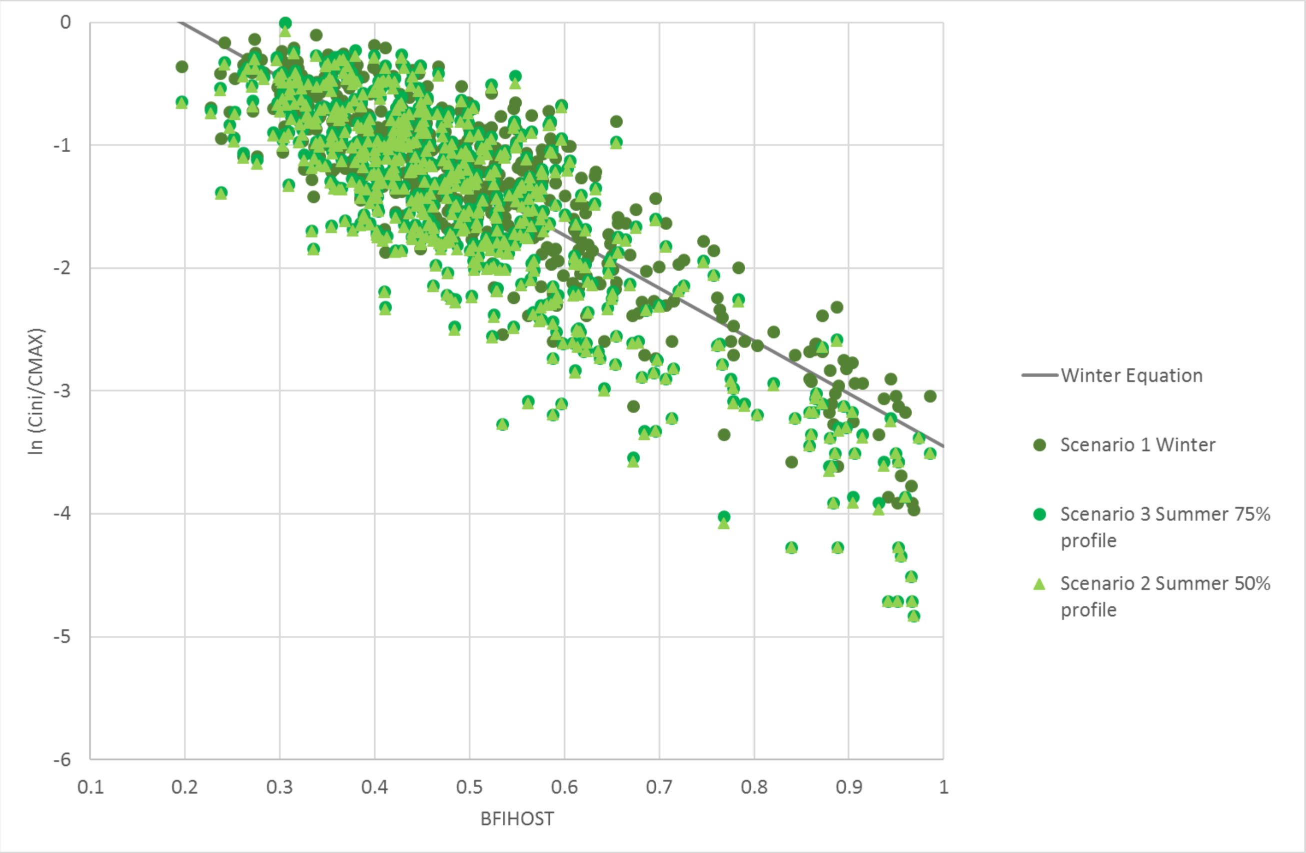


Figure 26 - Relationships between the calibrated values of C_{ini}/C_{max} for seasonal storms and BFIHOST

The scatter graph in Figure 26 plots the calibrated values of C_{ini}/C_{max} for seasonal storms and BFIHOST. The y-axis shows ln (C_{ini}/C_{max}) from -6 to 0. The x-axis shows BFIHOST from 0.1 to 1. The following elements are plotted:

- winter equation (grey line)
- scenario 1 winter (dark grey dots)
- scenario 3 summer 75% profile (mid green dots)
- scenario 2 summer 50% profile (light green triangles)

As discussed, the SCF values are a function of both SAAR and duration. The graph in Figure 26 demonstrates that significantly smaller C_{ini} values are required in permeable catchments (which also tend to be low SAAR catchments). These C_{ini} values are marginally smaller for a given catchment under the full summer design package (scenario 2) than scenario 3, which uses a 75% winter profile together with a summer SCF. The outcome that significantly lower values of summer C_{ini} are required for permeable catchments, and that this increases with increasing permeability is hydrologically intuitive. Soils on aquifer outcrops are permeable and drain freely and therefore the ability of the soils to accept water during a summer event will be higher.

The relationships between the ratio of the optimal summer C_{iniS} to the design winter C_{iniW} and catchment descriptors were explored. The rationale was to evaluate whether the differences could be estimated as a function of catchment descriptors such that C_{iniS} can be estimated from the C_{iniW} estimate to ensure that, within a catchment application, the estimates are consistent with one another. Eleven catchments with extremely low C_{ini} ratios were removed from the analysis (8002, 8005, 8010, 20002, 10003, 11004, 33048, 11001, 41023, 39027, 33052), all catchments in which the optimal initial conditions for both winter and summer were compensating for poor model performance.

The best relationships identified between this ratio and catchment descriptors were with the square root of the ratio of BFIHOST to SAAR. SAAR and BFIHOST are covariant and therefore using the ratio of BFIHOST to SAAR removes this covariant dependency while also simplifying the analysis to a univariate regression. Catchment scale was not found to be 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 are described by Equation 10 with the gradients, intercepts and measures of fit summarised on Table 6:

Equation 10 - Modelled relationship between summer C_{ini}, winter C_{ini}, *BFIHOST* and *SAAR*

$$\frac{C_{iniS}}{C_{iniW}} = m\left(\frac{BFIHOST}{SAAR}\right)^{0.5} + c$$

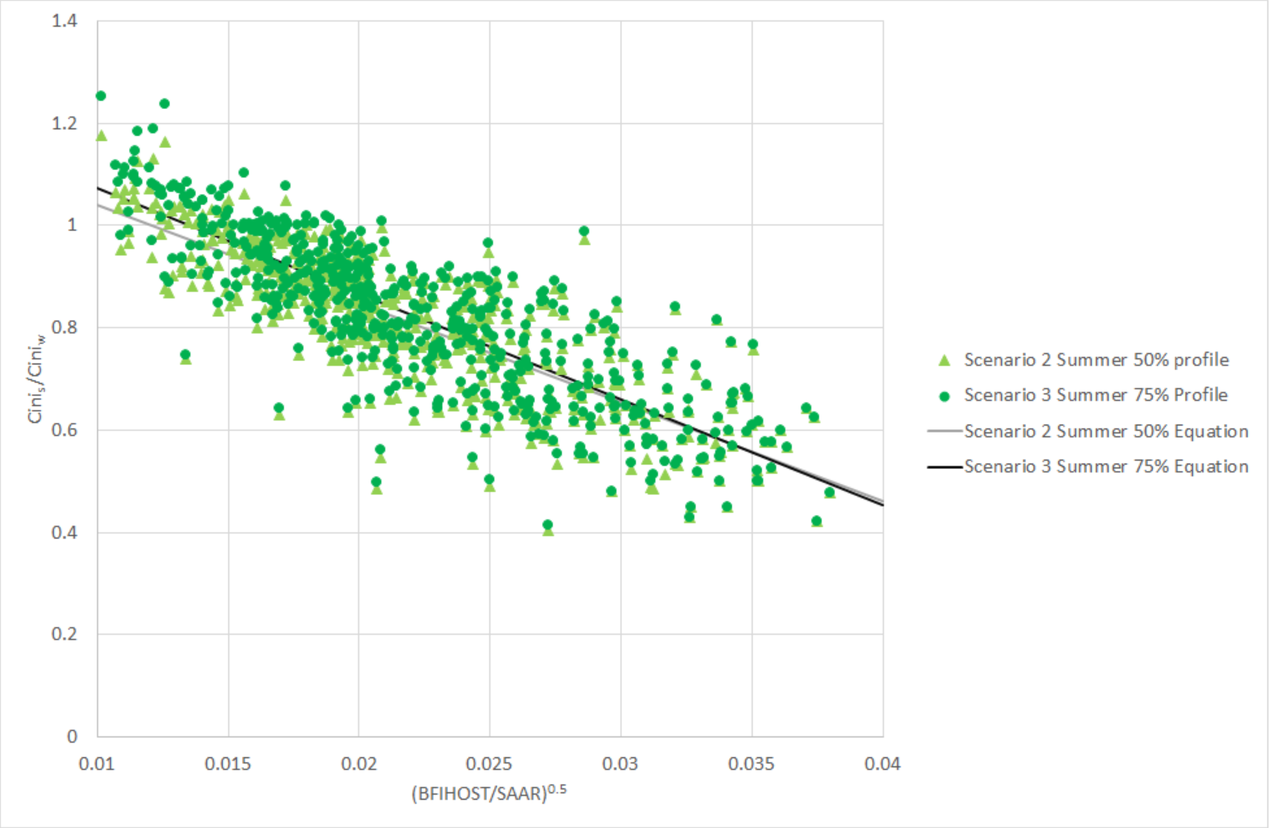


Figure 27 - The relationships between summer and winter C_{ini} and the ratio of BFIHOST to SAAR for summer storms with summer profiles and summer storms with winter profiles

The scatter graph in Figure 27 plots relationships between summer and winter C_{ini} and the ratio of BFIHOST to SAAR for summer storms with summer profiles and summer storms with winter profiles. The y-axis shows C_{inis}/C_{iniw}) from 0 to 1.4. The x-axis shows BFIHOST/SAAR$^{0.5}$ from 0.01 to 0.04. The following elements are plotted:

- scenario 2 summer 50% profile (light green triangles)
- scenario 3 summer 75% profile (green dots)
- scenario 2 summer 50% equation (grey line)
- scenario 3 summer 75% equation (black line)

Table 6 - Model parameters and fit statistics for estimating summer C_{ini} from the design winter C_{ini}

Scenario	m	C	R^2	fse
Summer 75% profile	-19.33	1.24	0.67	1.16
Summer 50% profile	-20.69	1.28	0.68	1.12

The results show that for very low values of the BFIHOST-SAAR ratio (that is, impermeable, very wet catchments) the C_{ini} summer is higher than the C_{ini} winter resulting in a ratio greater than 1. This is partly a consequence of using the winter design C_{ini} as the denominator (rather than the catchment specific winter value), but inspection of the raw results shows that this also occurs in some generally wetter catchments, where both the optimal winter and summer C_{ini} values are high, reflecting high saturation levels all year. This is a result of the interplay between the SCF ratios for winter and summer conditions. Inspecting the parameters shows that the gradient of the relationship is marginally higher when the 75% winter storm profile is used. The intercept is also marginally higher, suggesting that the summer C_{ini} values are marginally higher when a 75% winter profile is used rather than a 50% summer profile, and more as permeability and average annual rainfall increases.

Using these equations enables the summer C_{ini} to be estimated from the winter C_{ini} estimate. The estimated and calibrated C_{ini} values are shown for the winter and the two summer design scenarios on Figures 28 and 29.

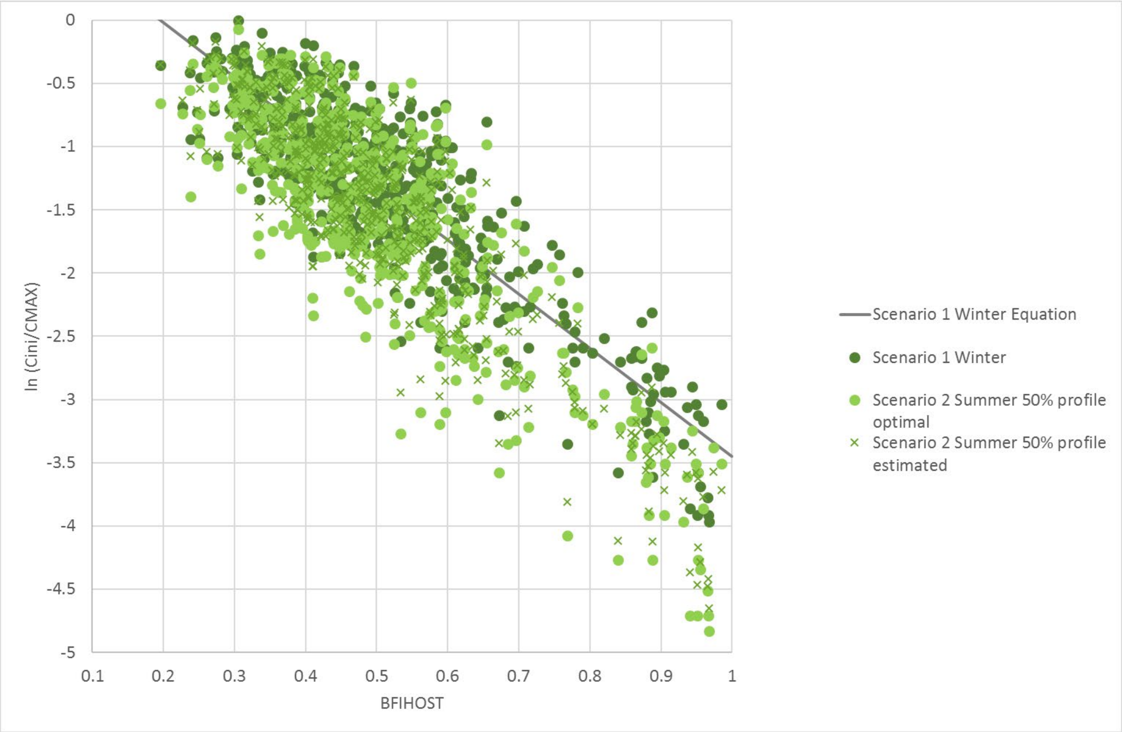


Figure 28 - Models for estimating design winter and summer C_{ini}/C_{max} values as a function of BFIHOST for the winter and scenario 2: summer conditions used together with the 50% summer profile

The y-axis on Figure 28 shows ln (C_{ini}/C_{max}) from -5 to 0. The x-axis shows BFIHOST from 0.1 to 1. The following elements are plotted:

- scenario 1 winter equation (grey line)
- scenario 1 winter (dark grey dots)
- scenario 2 summer 50% profile optimal (light green dots)
- scenario 2 summer 50% profile estimated (green crosses)

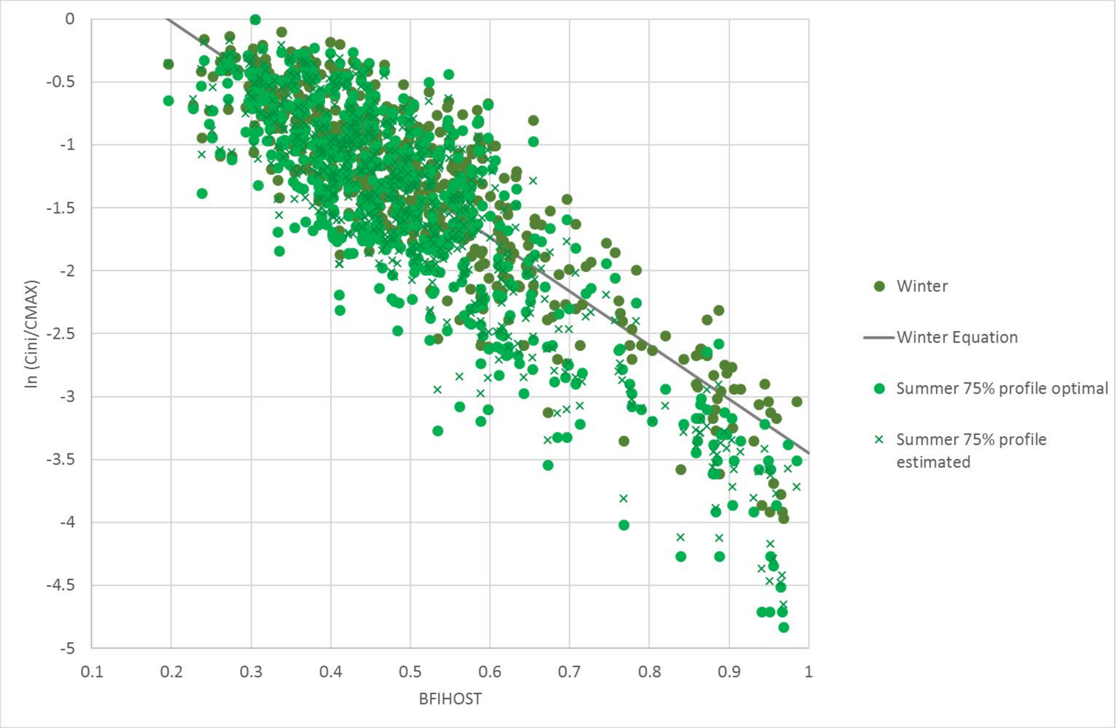


Figure 29 - Models for estimating design winter and summer C_{ini}/C_{max} values as a function of BFIHOST for the winter and scenario 3: summer conditions used together with the 75% winter profile

The y-axis on Figure 29 shows ln (C_{ini}/C_{max}) from -5 to 0. The x-axis shows BFIHOST from 0.1 to 1. The following elements are plotted:

- winter (dark green dots)
- winter equation (grey line)
- summer 75% profile optimal (bright green dots)
- summer 75% profile estimated (green crosses)

Optimisation of the urbanisation model

The approach adopted for re-optimising the urbanisation model was based on identifying the optimal values of IF and Tp multiplier required to minimise the ReFH2 model residuals for estimating QMED in urbanised catchments. Three optimisations were considered using the storm seasonality rules established in section 2.3. These were used together with the seasonal scenarios discussed in section 2.4. The application of the full winter scenario (Scenario 1) in all urban catchments irrespective of the seasonality rules is a control. The two summer scenarios, scenario 2 (50% summer profile) and scenario 3 (75% winter profile), test whether the assumption of a more peaked profile for a summer storm is supported by the data for very urbanised catchments.

For each of these scenarios the optimal values of values of IF and Tp were identified by minimising the estimation bias for the 54 catchments within the small catchment data set with $URBEXT_{2000}$ values greater than 0.15 and FARL > 0.9.

The IRF default value was retained as 0.7 since IF and IRF are covariant within the model and therefore only one needs to be modified. The choice of winter or summer C_{ini}, BF_0 and, where relevant, storm profiles for scenarios 2 and 3 was based on the rules established in the previous sections. In this application, the recommended duration is based on the as-rural duration estimated from the as-rural Tp estimate and SAAR.

Two classes of urbanisation have been considered: $0.15 \leq URBEXT_{2000} < 0.3$ and $URBEXT_{2000} \geq 0.3$. The rationale for choosing these class boundaries is based on the seasonality rules: 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.

As a baseline assessment, the influence of the choice of summer or winter storm has been assessed qualitatively by applying ReFH2 for each of the scenarios within the 54 catchments but treating the catchments as rural catchments. These results are presented in Figure 30 for the all-winter control case and for the two summer scenarios.

Inspecting the $URBEXT_{2000} \geq 0.3$ class (26 catchments), it is evident that the as-rural winter estimates are biased toward under prediction. Considering the two summer scenarios there is still a tendency to underestimate but it is much reduced. Furthermore, there is little difference between the as-rural estimates using the summer profile and those using the winter storm profile (together with the relevant estimate of summer C_{ini}).

The results in the $0.15 \leq URBEXT_{2000} < 0.3$ class interval (28 catchments) are less clear, with the winter as-rural estimate showing little evidence of bias. Considering the results under scenarios 2 and 3, there are only five catchments that meet the permeability criterion for a summer storm. Of these catchments, the as-rural estimates for three catchments have small residuals, while the other two have larger residuals. The residual for catchment 40016 under summer conditions was large enough that it masked any evaluation and therefore it was not considered further in the analysis. Of the five permeable catchments in this range that met the rule for using a summer event, the actual event seasonality was winter in three of the catchments and summer in two, one of which was 40016.

The influence of urbanisation on the QMED estimates in this class is not evident for this sample of small catchments and it is reasonable to suggest that using the seasonality rule for selecting summer storms is not supported by the results for the very small set of permeable catchments within this urbanisation class.

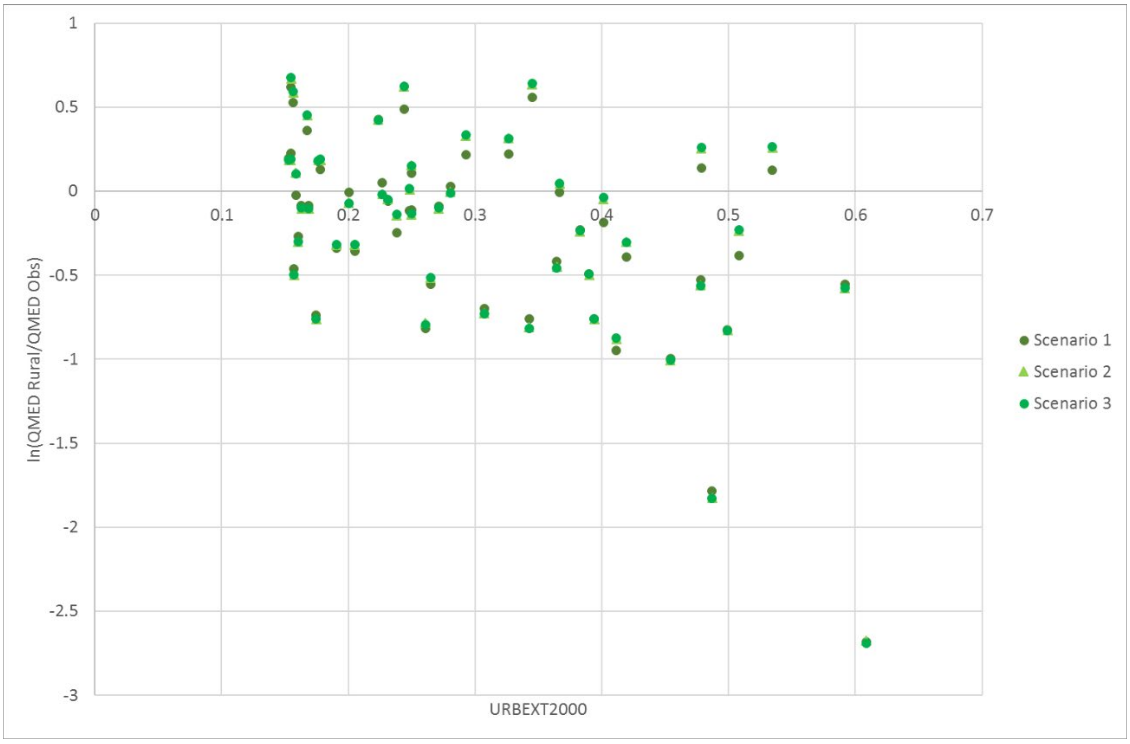


Figure 30 - As-rural QMED residuals for the three scenarios

The scatter graph in Figure 30 plots the results of applying ReFH2 for each of the scenarios within the 54 catchments but treating the catchments as rural catchments:

- scenario 1 (dark green dots)
- scenario 2 (green triangles)
- scenario 3 (bright green dots)

The y-axis shows ln (QMED rural/QMED Obs) from -3 to 1. The x-axis shows URBEXT_{2000}.

Given this outcome, the optimisation of the Tp multiplier and the IF parameter has focused on the heavily urbanised catchments ($\text{URBEXT}_{2000} \geq 0.3$). The absolute estimation bias results are presented for each scenario in Figures 31 to 33. The blue cells in these matrices are estimates that are reasonably unbiased, grading to red cells in which the results are either biased strongly toward underestimation (lower left) and to overestimation (upper right).

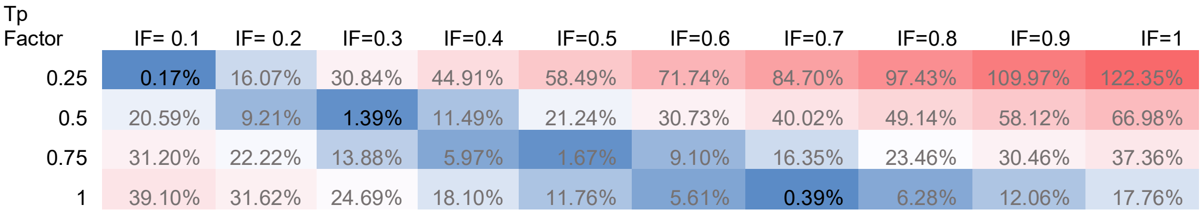
The matrices show the covariance of bias with the IF and the Tp factor; IF increases the impervious runoff volume while the Tp factor influences the timing and peakedness of the corresponding urban hydrograph. Small values of Tp factor result in a very peaked hydrograph, with a peak occurring before that of the as-rural hydrograph from the remainder of the catchment. One can therefore achieve a similar level of bias for different combinations of the two.

Considering the control winter storm (scenario 1), the optimal (minimum bias) solutions are either for high values of IF with a Tp factor of 0.75 or an IF of 0.5 and a Tp factor of 0.5. In all cases, the optimal biases are larger than observed for the two summer storm scenarios.

The trade-off between IF and Tp factor is very apparent for the two summer scenarios, but, in general, the lowest bias is found for values of IF of between 0.3 and 0.5 for the summer scenario using the less peaked 75% winter profile. However, the results for the 50% summer profile are still very low.

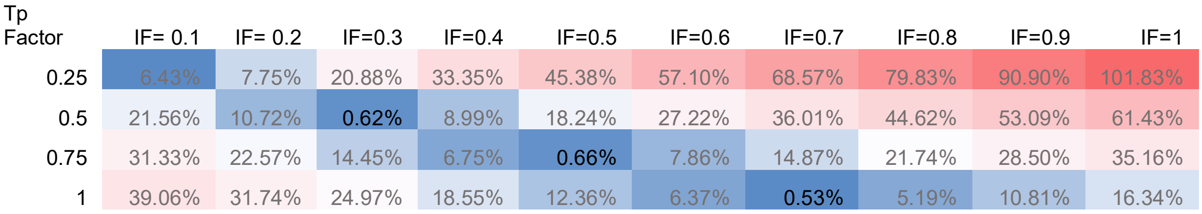
On this basis, the evidence suggests that either storm profile is acceptable to use and there is little to support moving away from the current values of IF = 0.3 and Tp factor of 0.5 as recommended within the current ReFH2 guidance (Wallingford HydroSolutions 2016).

The QMED model residuals for both scenarios 2 and 3 for IF = 0.3 and Tp factor = 0.5 are presented in Figure 34 for catchments with $URBEXT_{2000} \geq 0.3$. As-rural results are presented for the catchments with $0.15 \leq URBEXT_{2000} < 0.3$ for comparison, illustrating that the urban residuals are unbiased with similar levels of unexplained variation.



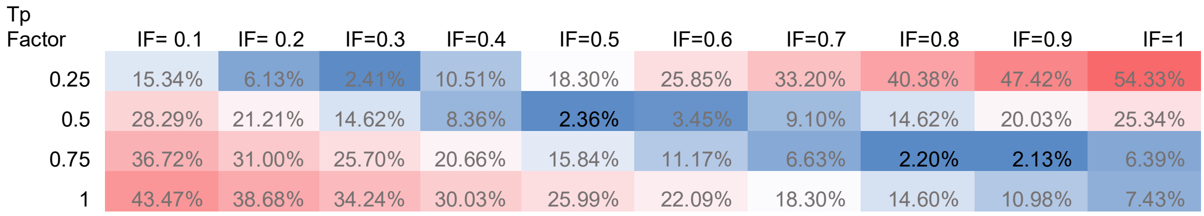
Tp Factor	IF= 0.1	IF= 0.2	IF=0.3	IF=0.4	IF=0.5	IF=0.6	IF=0.7	IF=0.8	IF=0.9	IF=1
0.25	0.17%	16.07%	30.84%	44.91%	58.49%	71.74%	84.70%	97.43%	109.97%	122.35%
0.5	20.59%	9.21%	1.39%	11.49%	21.24%	30.73%	40.02%	49.14%	58.12%	66.98%
0.75	31.20%	22.22%	13.88%	5.97%	1.67%	9.10%	16.35%	23.46%	30.46%	37.36%
1	39.10%	31.62%	24.69%	18.10%	11.76%	5.61%	0.39%	6.28%	12.06%	17.76%

Figure 31 - Matrix of absolute bias illustrating the relationship between IF, Tp factor and absolute bias for scenario 3 (summer storm, 50% (FSR summer) profile)



Tp Factor	IF= 0.1	IF= 0.2	IF=0.3	IF=0.4	IF=0.5	IF=0.6	IF=0.7	IF=0.8	IF=0.9	IF=1
0.25	6.43%	7.75%	20.88%	33.35%	45.38%	57.10%	68.57%	79.83%	90.90%	101.83%
0.5	21.56%	10.72%	0.62%	8.99%	18.24%	27.22%	36.01%	44.62%	53.09%	61.43%
0.75	31.33%	22.57%	14.45%	6.75%	0.66%	7.86%	14.87%	21.74%	28.50%	35.16%
1	39.06%	31.74%	24.97%	18.55%	12.36%	6.37%	0.53%	5.19%	10.81%	16.34%

Figure 32 - Matrix of absolute bias illustrating the relationship between IF, Tp factor and absolute bias for scenario 2 (summer storm, 75% (FSR winter) profile)



Tp Factor	IF= 0.1	IF= 0.2	IF=0.3	IF=0.4	IF=0.5	IF=0.6	IF=0.7	IF=0.8	IF=0.9	IF=1
0.25	15.34%	6.13%	2.41%	10.51%	18.30%	25.85%	33.20%	40.38%	47.42%	54.33%
0.5	28.29%	21.21%	14.62%	8.36%	2.36%	3.45%	9.10%	14.62%	20.03%	25.34%
0.75	36.72%	31.00%	25.70%	20.66%	15.84%	11.17%	6.63%	2.20%	2.13%	6.39%
1	43.47%	38.68%	34.24%	30.03%	25.99%	22.09%	18.30%	14.60%	10.98%	7.43%

Figure 33 - Matrix of absolute bias illustrating the relationship between IF, Tp factor and absolute bias for scenario 1 (winter storm, 75% winter profile)

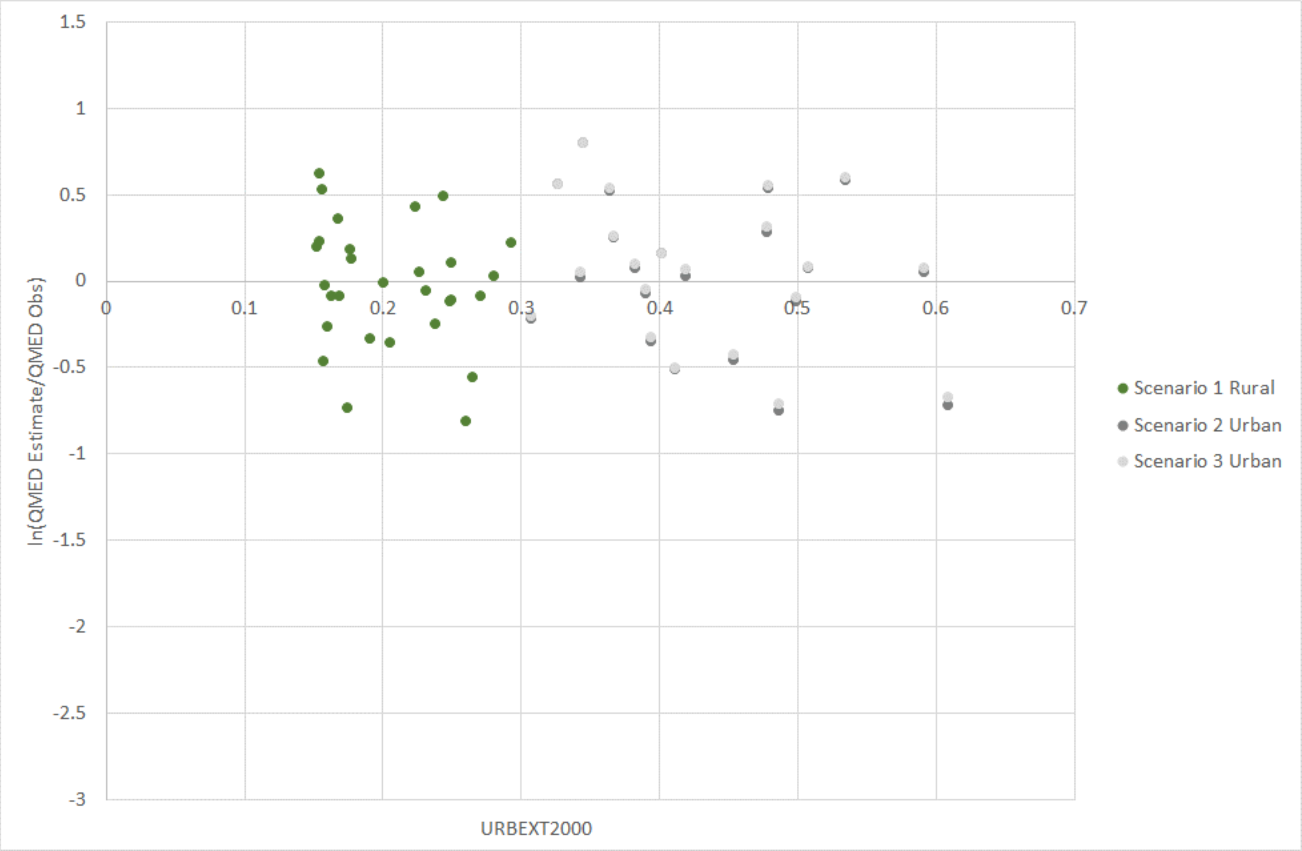


Figure 34 - QMED log residuals following the application of the revised urbanisation procedures in urban catchments

The y-axis on Figure 34 shows ln (QMED estimate/QMED Obs) from -3 to 1.5. The x-axis shows $URBEXT_{2000}$. The following elements are plotted:

- scenario 1 rural (green dots)
- scenario 2 urban (dark grey dots)
- scenario 3 urban (light grey dots)

2.5 Summary and research recommendations

This analysis has demonstrated that the influence of urbanisation on the index flood QMED is only apparent at levels of urbanisation greater than $URBEXT_{2000}$ = 0.3. This is supported both by the analysis of as-rural QMED model residuals and the analysis of seasonality in AMAX data. The latter analysis demonstrated that influence of urbanisation on seasonality was distinctly evident in these heavily urbanised catchments through a shift towards summer storm events dominating the AMAX series, and in particular the largest events in the series.

The analysis has shown that using the summer SCF values within ReFH means using a summer $C_{ini,}$ and that this can be estimated directly from the winter design estimate. The differences between the winter and optimal summer C_{ini} values within catchments is strongly related to the relationship between catchment permeability (as represented by BFIHOST) and catchment climate (as represented by SAAR). The optimal summer C_{ini} values are also slightly influenced by the choice of storm rainfall profile (considering the FSR 75% winter and 50% summer profiles).

Using a summer storm event within catchments with $URBEXT_{2000} \geq 0.3$ was more effective in minimising model residuals than using a winter storm. Considering the differences between the two summer storm event scenarios tested, there is some evidence that the 50% summer profile is too peaked and that using the 75% profile is slightly better, although this is marginal. The analysis has confirmed that the ReFH2 defaults of Tp factor = 0.5 and IF = 0.3 are appropriate and, given the covariance of model residual bias with these two parameters, alternative combinations of these parameters should only be used with caution.

A more challenging problem is urbanised catchments with levels of urbanisation of $URBEXT_{2000} < 0.3$. The seasonality analysis provided evidence that for permeable catchments with $URBEXT_{2000}$ values in the range $0.15 \leq URBEXT_{2000} < 0.3$, the large floods tended to be summer events. This was against the backdrop that, for all other catchment types below $URBEXT_{2000} < 0.3$, the large floods were dominated by winter events.

However, the analysis of log residuals showed small levels of estimation bias in the winter as-rural estimates for catchments lying in the range $0.15 \leq URBEXT_{2000} < 0.3$ and in both the winter and summer as-rural estimates for the small number of permeable catchments in this range. This suggests that there is no justification for incorporating the influence of urbanisation in estimates below a threshold of $URBEXT_{2000}$ value of 0.3.

With this outcome applying the urbanisation model in ReFH2 may lead to an over-estimate of runoff.

It is also difficult to advise whether summer storms should be used for permeable catchments in this urbanisation class. The seasonality signal across all catchments did suggest this to be appropriate, but the results for the four permeable small catchments in this class suggested that the influence of urbanisation could not be detected.

This lack of evidence for the impact of urbanisation below a threshold of 0.3 is also observed when considering estimation residuals from the FEH statistical method catchment descriptor equation for estimating QMED (Wallingford HydroSolutions, 2016) and therefore is not a feature of the ReFH modelling methodology.

What this might suggest is that at lower levels of urbanisation, unless the urbanisation is adjacent to a significant watercourse, and impervious surfaces drain to the watercourses, the urban surface runoff rates are attenuated before the runoff impacts on the scale of gauged catchments considered.

This analysis has highlighted that the empirical choice of storm profile was based on earlier methods, both in terms of design rainfall model and rainfall runoff model. Nevertheless, although the analysis has demonstrated that the 50% summer storm profile is too peaked for current design methods, the differences are small. On balance, the 75% winter storm profile may be the more appropriate profile for small catchment urbanisation problems, and, by extension, for sustainable urban drainage design.

The potential issues of ‘connectivity’ of urban impervious surfaces to the stream network at lower levels of urbanisation is an area worth investigating further. This is the subject of ongoing research at the Centre of Ecology & Hydrology, building upon the work of Mejía and Moglen (2009).

2.6 Recommendations for use

The following recommendations are made.

For catchment application:

- if $URBEXT_{2000}$ is ≥ 0.3:
    - a summer storm should 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 should be used with the 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 $0.15 \leq URBEXT_{2000} < 0.3$:
    - the catchment should, by default, be treated as a rural catchment with a winter storm
    - the urbanised results can be 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 ≥ 800 mm. 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.

3. Estimating Tp for small-scale applications

3.1 Introduction

The Tp is the unit hydrograph time-to-peak parameter; the smaller the Tp, the peakier the unit hydrograph and, by definition, the final event hydrograph for a given event duration. The value of Tp is used in estimating the recommended duration within the design event package; smaller values of Tp correspond to shorter recommended event durations.

The original calibration of the ReFH design model was carried out using rainfall data and streamflow data at an hourly time step. Therefore, the lowest estimate of Tp that can be resolved from this time step has a value of one hour. Within the ReFH2 design package, Tp can be estimated from catchment descriptors. Two alternative equations are provided:

- one for applications within catchments that have a defined drainage network (using the mean drainage path length (DPLBAR) descriptor)
- one for plot-scale application using contributing area instead of DPLBAR

These catchment descriptor equations can produce estimates of Tp that are less than one hour. However, as these are not theoretically valid, a minimum value of one hour is set within the ReFH2 software.

The evaluation of the ReFH modelling framework through calibration using plot-scale experimental data sets for this project suggested that the ReFH model framework is appropriate for simulating runoff generation from the relatively impermeable plots. The outcomes obtained by applying the ReFH2 design package with Tp constrained to a lower limit of one hour confirmed that the design package is also appropriate for application at the plot scale. The results obtained using the full design package and the plot-scale design package yield similar results, but using the plot-scale equations enables the method to be applied directly where there is no definable drainage network.

Unfortunately, only two plot-scale data sets were available for the analysis of plot-scale runoff carried out earlier in the project. This section reviews whether the theoretical lower limit of one hour for Tp is appropriate for small catchments and for wider plot-scale application. It should be noted that the Tp multiplier within the urban modelling procedures is generally less than unity, and therefore the effective Tp for the urban extents may be less than one hour depending on the value of the as-rural estimate of Tp.

For urban catchments, the default parameterisation of the urban modelling procedures was developed using the rural Tp recommended duration.

3.2 Data

The AMAX series for the catchments within the final small catchment data set of 217 catchments classified as being suitable for estimating QMED has been used for this assessment. The data set was then filtered using the following criteria:

1. FARL > 0.9
2. $URBEXT_{2000}$ < 0.03 (essentially rural)

This provides a data set of 146 catchments. The $URBEXT_{2000}$ criterion, selecting essentially rural catchments, is a very conservative one; assessments of model residuals for both ReFH2 and the statistical methods within WINFAP across both the small catchments and NRFA peak flow data sets would suggest that the influence of urbanisation is not detectable for urbanised catchments with less than the heavily urbanised threshold value of $URBEXT_{2000}$ > 0.15.

The estimates of peak flows within both the FEH statistical and ReFH2 methods are sensitive to the estimate of contributing area. Table 7 shows a list of stations that were removed as outliers, therefore reducing the data set to 143 catchments. These were clear outliers within the applications of both the ReFH2 and WINFAP methodologies indicating that there may be errors in the assumption that the topographic catchment area is a good estimate of the area contributing to runoff as measured at the gauging station.

Table 7 - Outlier stations removed from the analysis. ReFH2 estimates use the FEH13 data set

NRFA No.	River	Station	Notes	QMED observed (m^3s^{-1})	QMED equation (m^3s^{-1})	QMED ReFH2 (m^3s^{-1})
27032	Hebden Beck	Hebden	This is a partially karstic catchment and the NRFA note that the true drainage area is unknown.	3.93	25.6	29.43
205034	Woodburn	Control	Catchment area is very small (0.2 km^2). This is located downstream of a concrete channel which connects two reservoirs; therefore an accurate assessment of the catchment area is difficult.	0.12	3.11	3.4
65008	Peris	Nant Peris	A very responsive catchment. Issues are noted by the NRFA due to the non-standard concrete control and extensive gravel accumulation.	33.6	13.8	16.7

3.3 Estimating Tp within ReFH2

The catchment and plot-scale equations for estimating Tp

As discussed, and described in detail within the ReFH2 technical guidance, the ‘as-rural’ time-to-peak parameter can be estimated within ReFH2 using either the catchment or plot-scale equations. In catchments greater than 0.5 km^2 (that is, the scale of the drainage network defined within the FEH Web Service; CEH (2015)) it is generally recommended that the catchment equation should be used. In very small (<0.5 km^2) catchments, or for plot-scale assessments, the plot-scale equation should be used. The forms of the equations are presented in Equations 11 and 12 respectively. Within the plot-scale equations AREA (km^2) and SAAR (standard period average annual rainfall for 1961 to 1990, mm) replace DPLBAR (mean of distances between each 50 m node on a grid and the catchment outlet, km) and DPSBAR (mean of all the inter-nodal slopes, mkm^{-1}) as measures of catchment size and slope/wetness. Area is strongly correlated with DPLBAR in small catchments and DPSBAR and SAAR are also strongly correlated. PROPWET (proportion of time when the soil moisture deficits were equal to or below 6 mm for the period 1961 to 1990) is included in both equations.

Note that the potential impact of urban developments on Tp is incorporated explicitly within the ReFH2 software and therefore does not feature within the as-rural estimate of Tp.

Equation 11 – Relationship between ReFH2 parameter *Tp* and catchment descriptors (for catchments)

$$Tp = aPROPWET^{b}DPLBAR^{c}DPSBAR^{e}$$

Equation 12 – Relationship between ReFH2 parameter *Tp* and catchment descriptors (for plots)

$$Tp = aPROPWET^{b}AREA^{c}SAAR^{e}$$

Relationships between the magnitude of Tp estimates and component catchment descriptors

The relationships between Tp estimated from the catchment (Equation 11) and plot-scale (Equation 12) equations and the relevant catchment descriptors for the catchments considered have been investigated to identify the types of catchments where the estimates of Tp are likely to be less than 1. These relationships are presented in Figures 35 to 37 for the catchment equation for Tp and component descriptors.

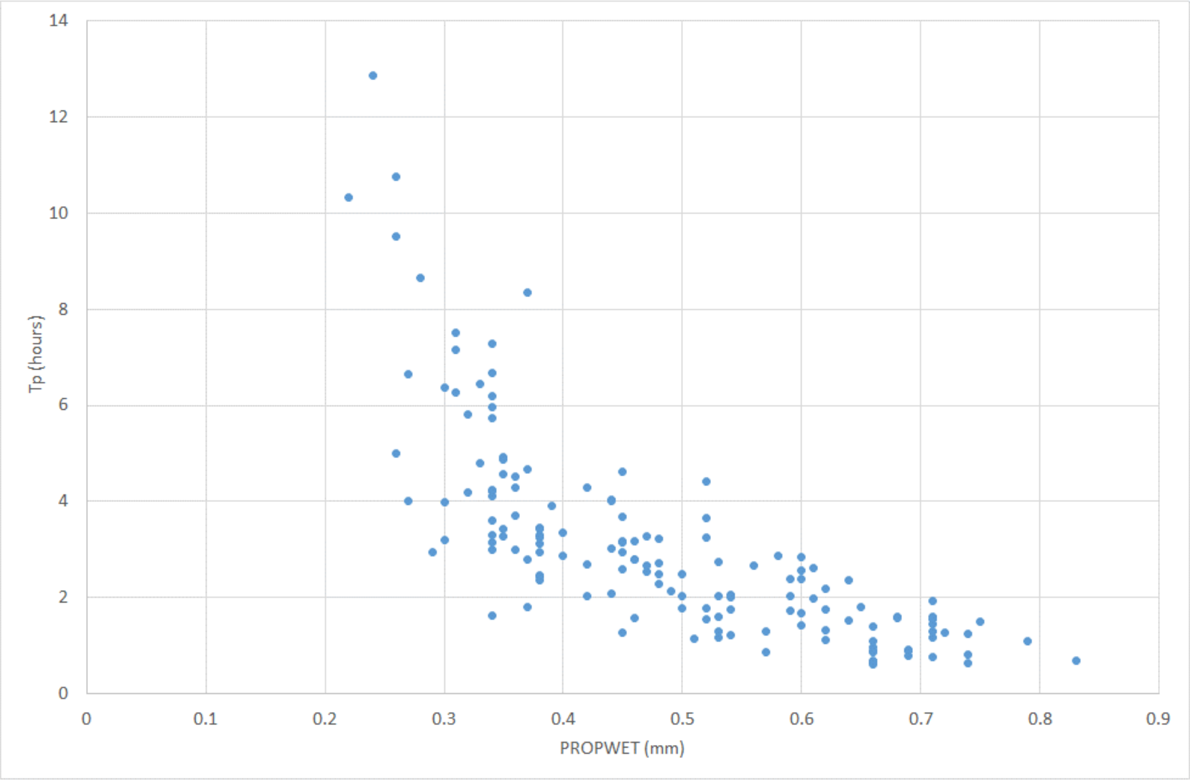


Figure 35 - The relationship between Tp estimated using the catchment equation and PROPWET

The y-axis on Figure 35 plots Tp (from 0 to 14 hours). The x-axis plots PROPWET (from 0 to 0.9 mm).

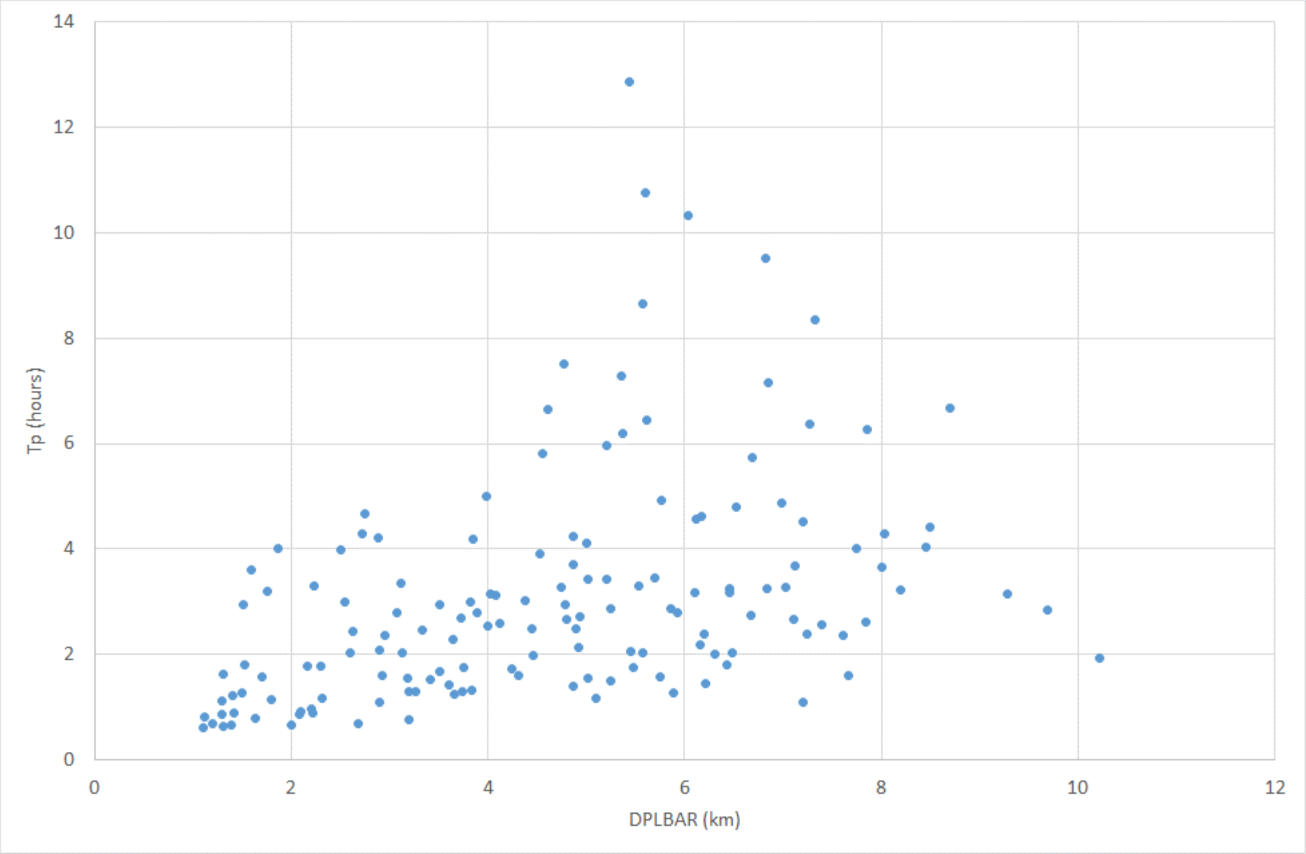


Figure 36 - The relationship between Tp estimated using the catchment equation and DPLBAR

The y-axis on Figure 36 plots Tp (from 0 to 14 hours). The x-axis plots DPLBAR (from 0 to 12 km).

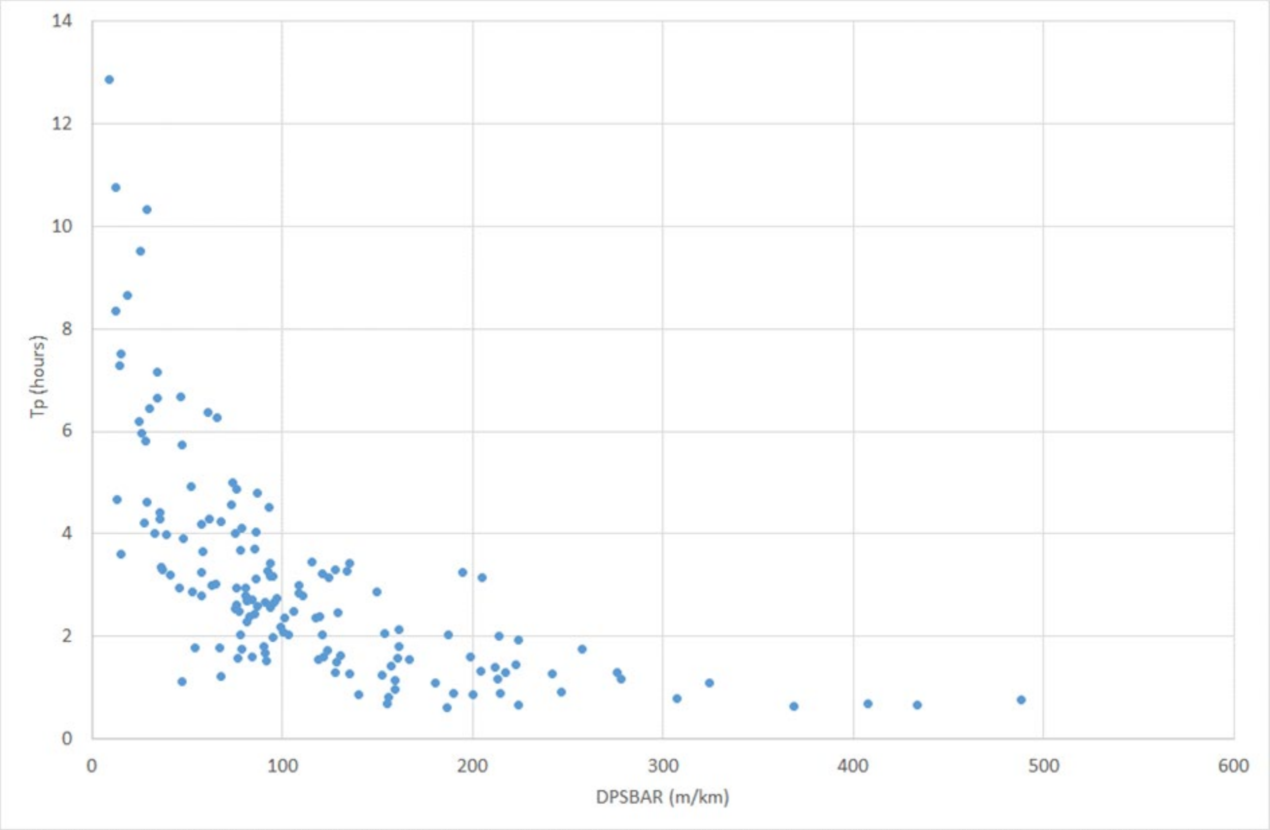


Figure 37 - The relationship between Tp estimated using the catchment equation and DPSBAR

The y-axis on Figure 37 plots Tp (from 0 to 14 hours). The x-axis plots DPSBAR (from 0 to 600 m/km).

These illustrate that the strongest relationships are between Tp and DPSBAR and PROPWET. These two parameters indicate that steeper catchments and those without large soil moisture deficits have a lower estimated Tp value that might result in estimates of Tp less than 1. In addition, as the DPLBAR becomes smaller, Tp tends to reduce and the influence of scale (as represented by DPLBAR) would appear to become more dominant as the variation in Tp for a given value of DPLBAR reduces. However, it should be noted that drier and lower gradient catchments can occur over a wide range of catchment sizes depending on location, therefore giving the apparent lower association between DPLBAR and estimated Tp.

The relationships between Tp and the relevant plot-scale descriptors are presented in Figures 38 to 40. These illustrate that SAAR and PROPWET have the greatest influence on the estimate of Tp within the plot-scale equation, confirming the patterns observed for the catchment equation. The same patterns are observed with AREA as for the catchment equation.

It can therefore be concluded that it is on steep, wet upland catchments that the catchment descriptor equations may estimate Tp values of less than 1 and that the size of the catchment is not relevant.

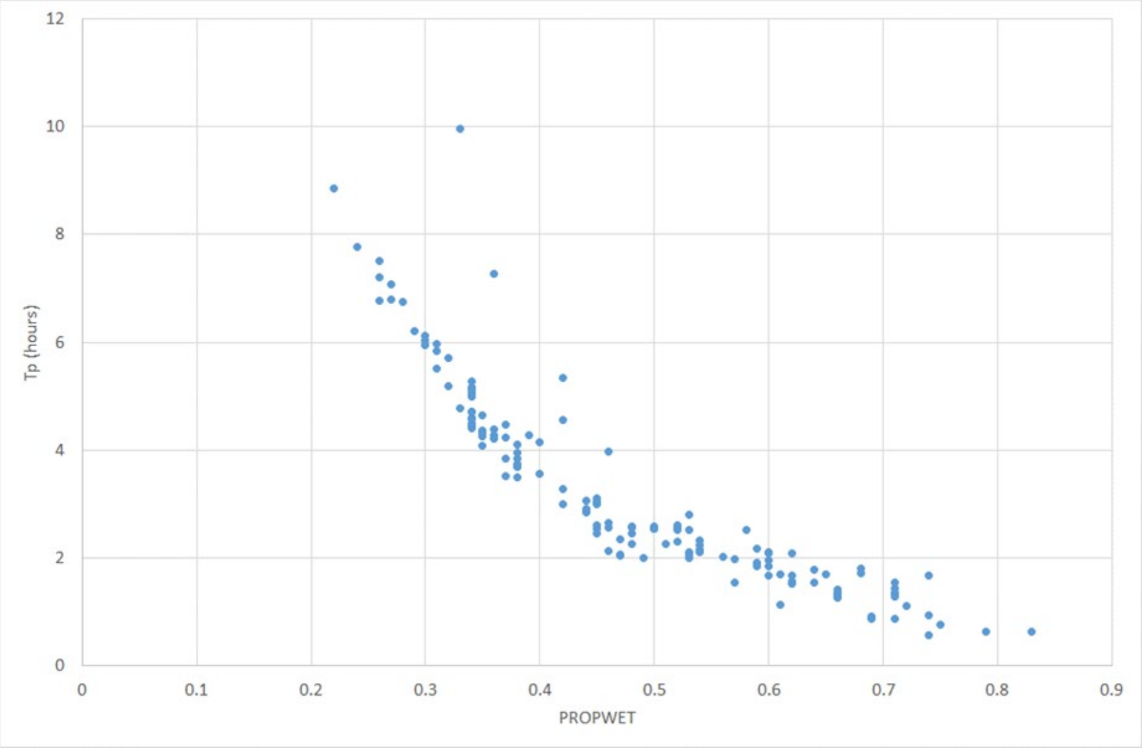


Figure 38 - The relationship between Tp estimated using the plot-scale equation and PROPWET

The y-axis on Figure 38 plots Tp (from 0 to 12 hours). The x-axis plots PROPWET from 0 to 0.9.

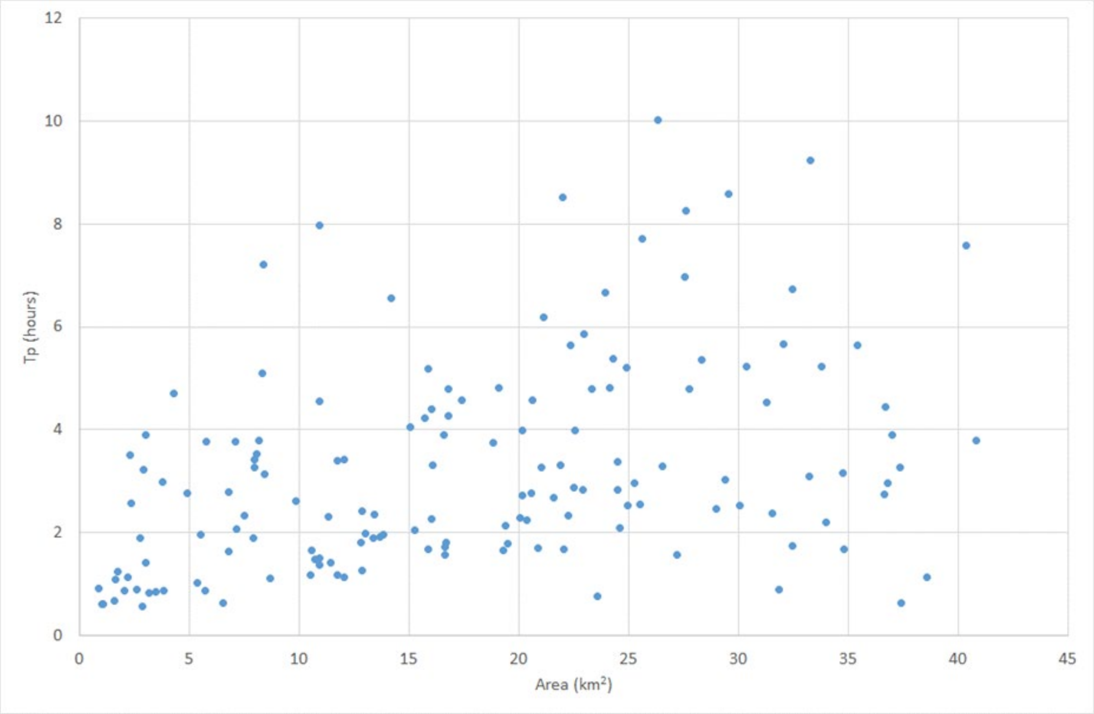


Figure 39 - The relationship between Tp estimated using the plot-scale equation and AREA

The y-axis on Figure 39 plots Tp (from 0 to 12 hours). The x-axis plots area (from 0 to 45 km^2).

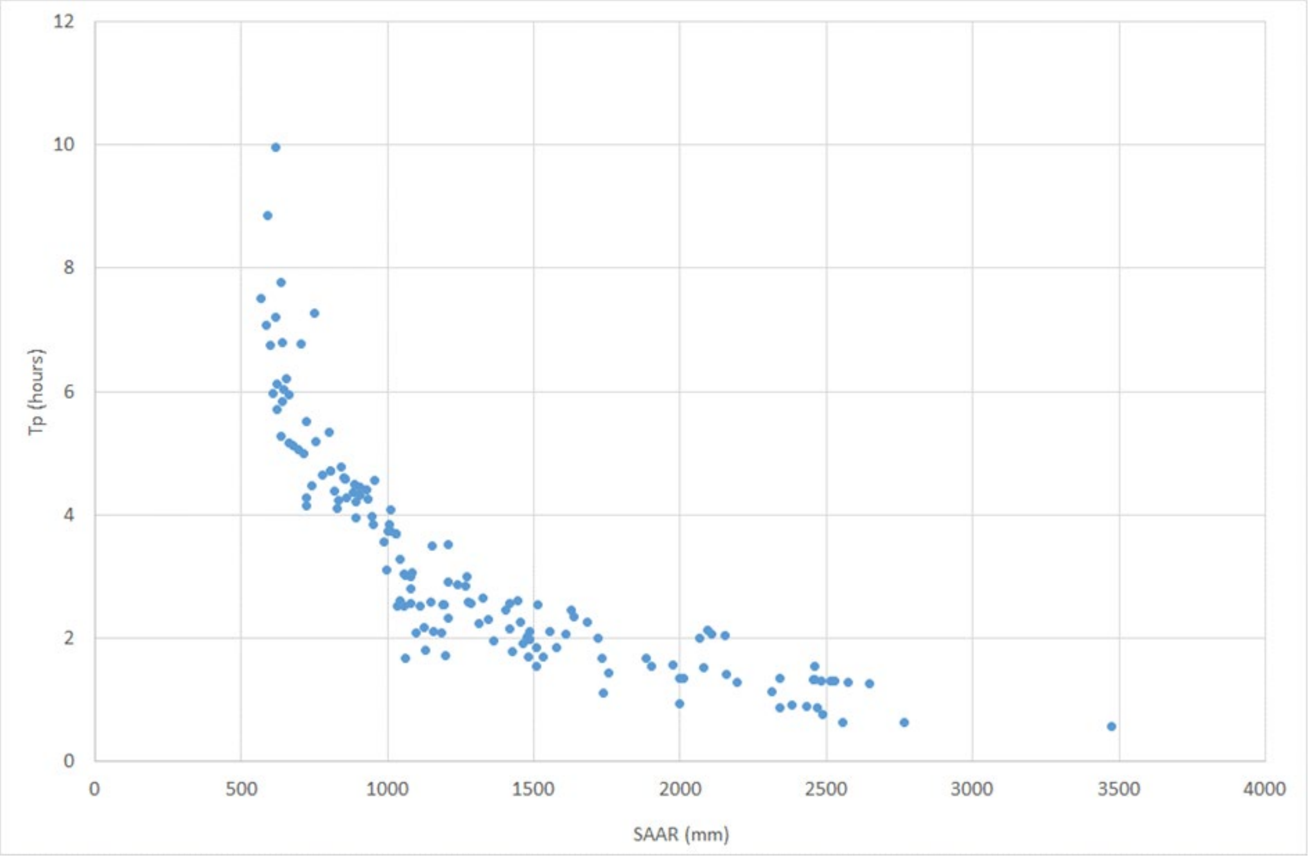


Figure 40 - The relationship between Tp estimated using the plot-scale equation and SAAR

The y-axis on Figure 40 plots Tp (from 0 to 12 hours). The x-axis plots SAAR (from 0 to 4000mm).

3.4 Catchment-scale assessment of the sensitivity of peak flow estimation to a bounding lower limit to Tp

The implication of limiting Tp to a lower limit of one hour is relevant to both applying ReFH2 within small catchments and using ReFH2 for plot-scale assessment of runoff rates. The sensitivity of estimating QMED and Q100 to the setting of a Tp lower limit of one hour was evaluated in a catchment context. The plot-scale context is assessed in section 3.5.

Methodology

The focus of this analysis was estimating QMED and Q100 peak flows using the ReFH2 design package for the 143 catchments in the data set. For each catchment, Tp was calculated using the catchment and plot-scale equations. The peak flow was then estimated using the design rainfall inputs from the FEH13 rainfall model. Peak flow estimates were also generated using a Tp of one hour for those catchments in which the estimates of Tp were less than one hour.

The peak flow estimates were compared with the local QMED (2-year return period) estimates derived from the gauged records for each catchment and the pooled estimate of the Q100 (100-year peak flow estimate). The Q100 pooled estimates were based on the growth factors generated using the improved FEH statistical method multiplied by the local QMED value. Enhanced single-site estimation was not used as only one station that had an estimate of Tp less than 1 was designated as being suitable for pooling. The sets of residuals were compared using the geometric bias and factorial standard error (fse), noting that the Q100 estimates are a comparison of methods rather than a comparison of model estimates and estimates of observed data.

Results

The list of catchments in which the catchment descriptor estimates of Tp would be limited to one hour are presented in Table 8.

Table 8 - List of stations for which Tp is limited

Catchment no.	River	Station name	Tp limited in catchment equation	Tp limited in plot-scale equation
18020	Loch Ard Burn	Duchray	Y	Y
54090	Tanllwyth	Tanllwyth Flume	Y	Y
54091	Severn	Hafren Flume	Y	Y
54092	Hore	Hore Flume	Y	Y
54097	Hore	Upper Hore Flume	Y	Y
55033	Wye	Gwy Flume	Y	Y
55035	Iago	Iago Flume	Y	Y
64011	Afon Cerist	Llawr Cae	Y	No data
69042	Ding Brook	Naden Reservoir	Y	No data
80003	White Laggan Burn	Loch Dee	Y	Y
80004	Green Burn	Loch Dee	Y	Y
80005	Dargall Lane	Loch Dee	Y	Y
86001	Little Eachaig	Dalinlongart	No data	Y
87801	Allt Uaine	Intake	Y	Y

Catchment no.	River	Station name	Tp limited in catchment equation	Tp limited in plot-scale equation
89004	Strae	Glen Strae	No data	Y
89007	Abhainn a'Bhealaich	Braevallich	No data	Y
91802	Allt Leachdach	Intake	Y	Y

Table 9 presents the relevant catchment descriptors for catchments in which the catchment descriptor equation estimates would be limited to one hour, together with information relating to the full data set. Note that for PROPWET, DPLBAR and DPSBAR, the results relating to catchments limited using the catchment equation are presented. For AREA and SAAR, the results relating to catchments limited using the plot-scale equation are presented.

Table 9 - Catchment descriptors for Tp-limited and full catchment datasets

Catchment descriptor	Tp-limited (median)	Tp-limited (min)	Tp-limited (max)	Full (median)	Full (min)	Full (max)
PROPWET (-)	0.66	0.57	0.83	0.46	0.22	0.83
DPLBAR (km)	1.53	1.1	2.68	4.78	1.1	10.22
DPSBAR (m/km)	207	134	433	91	8.8	433
AREA (km^2)	3.19	0.86	37.38	16.8	0.86	40.8
SAAR (mm)	2488	2000	3473	1132	567	3473

The bias and fse obtained using the catchment-scale Tp and Tp ≥ one hour (Tp1) within those catchments where Tp would be limited are presented in Table 10 for those catchments in which the catchment scale estimate of Tp would be less than one hour, and in Table 11 for the catchments in which the plot-scale estimates of Tp would be less than one hour. In both cases, the QMED from catchment descriptors (QMED CDS) is also presented for comparison purposes.

The results are presented graphically in Figures 41 to 44. Figure 41 presents the results for the limited catchments alongside the whole catchment data set for context. Note that there are a different number of catchments within the data sets for each Tp estimation method (14 for the catchment-scale Tp equation and 15 for the plot-scale Tp equation) as shown in Tables 10 and 11.

Table 10 - Measures of fit obtained using the catchment-scale Tp and Tp=1 hour (Tp1) within those catchments where Tp would be limited to 1

Statistic	QMED Tp1	QMED Tp	Q100 Tp1	Q100 Tp	QMED CDS
No.	14	14	14	14	14
Bias	1.20	1.48	1.26	1.56	1.28
FSE	1.52	1.75	1.57	1.83	1.45

Table 11 - Measures of fit obtained using the plot-scale Tp and Tp=1 hour (Tp1) within those catchments where Tp would be limited to 1

Statistic	QMED Tp1	QMED Tp	Q100 Tp1	Q100 Tp	QMED CDS
No.	15	15	15	15	15
Bias	1.19	1.51	1.25	1.58	1.17
FSE	1.50	1.80	1.54	1.72	1.37

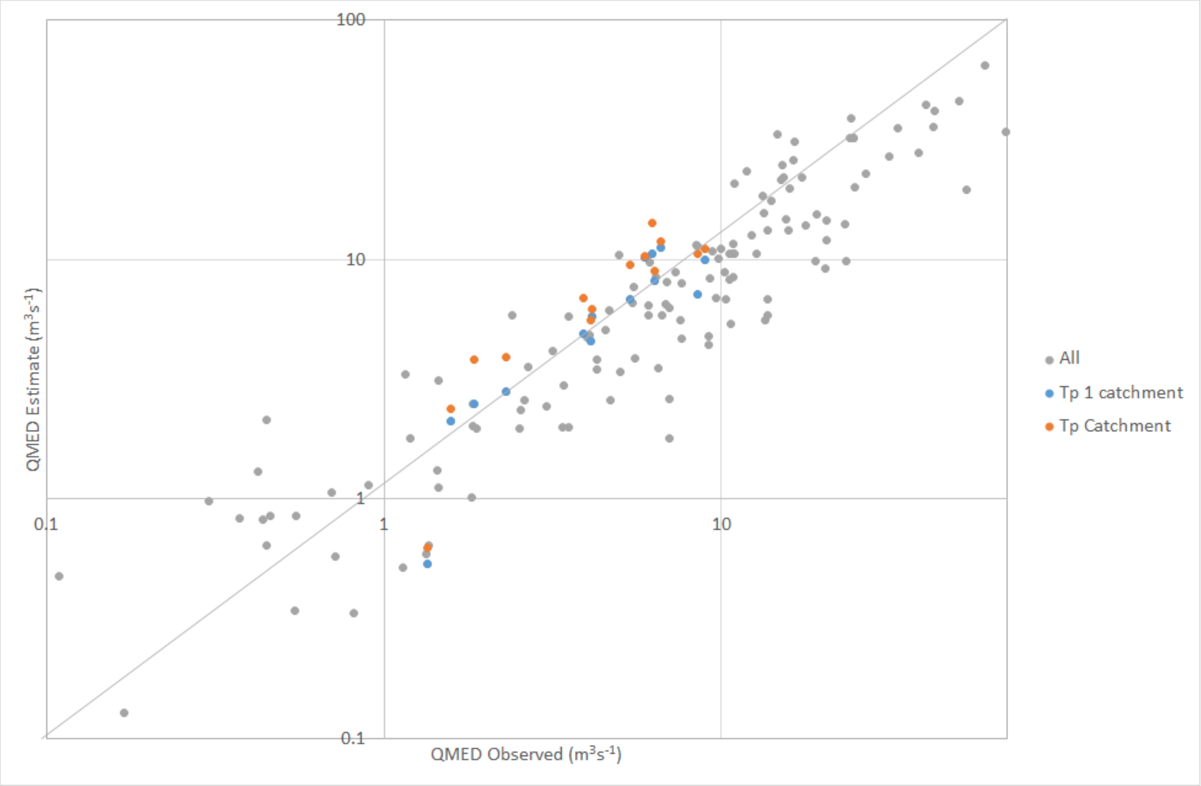


Figure 41 - The observed QMED and that estimated using the catchment Tp equation for catchments where Tp is limited

The y-axis of Figure 41 shows the estimated QMED (m^3s^{-1}). The x-axis shows the observed QMED (m^3s^{-1}). The small catchment data set is presented for comparison.

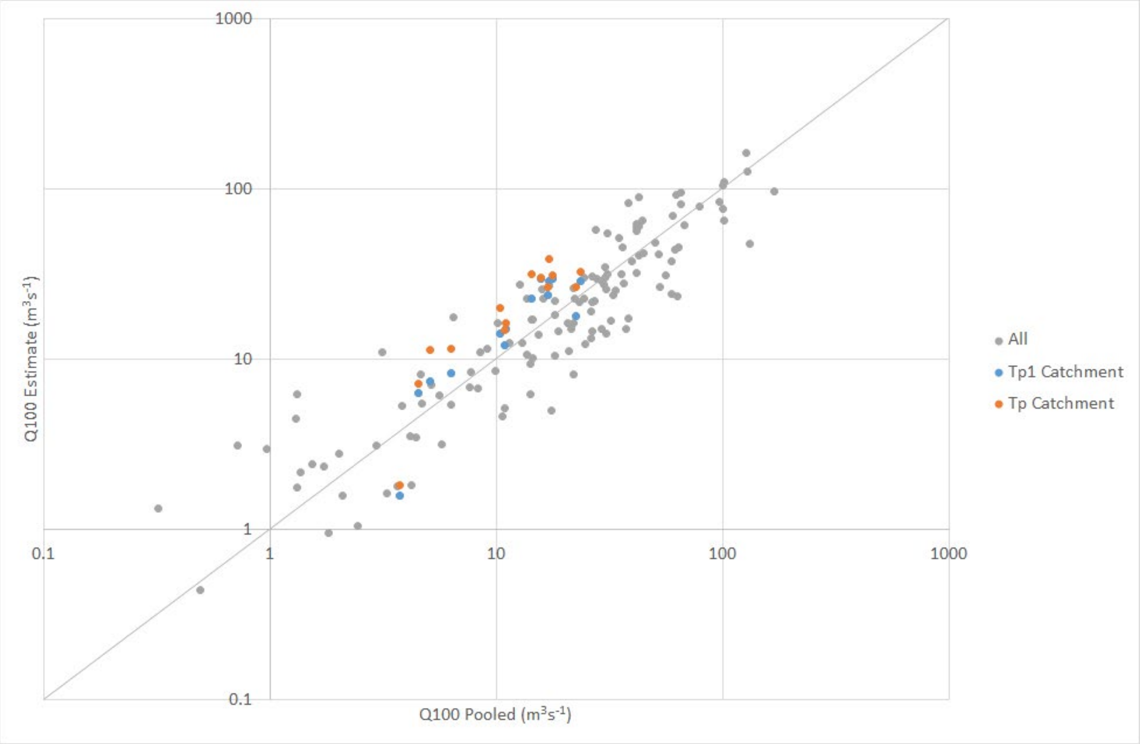


Figure 42 - The Q100 estimated using the catchment Tp equation and the pooled statistical estimate for catchments where Tp is limited

The y-axis of Figure 42 shows the Q100 estimate (m^3s^{-1}). The x-axis shows the Q100 pooled statistical estimate (m^3s^{-1}). The small catchment data set is presented for comparison.

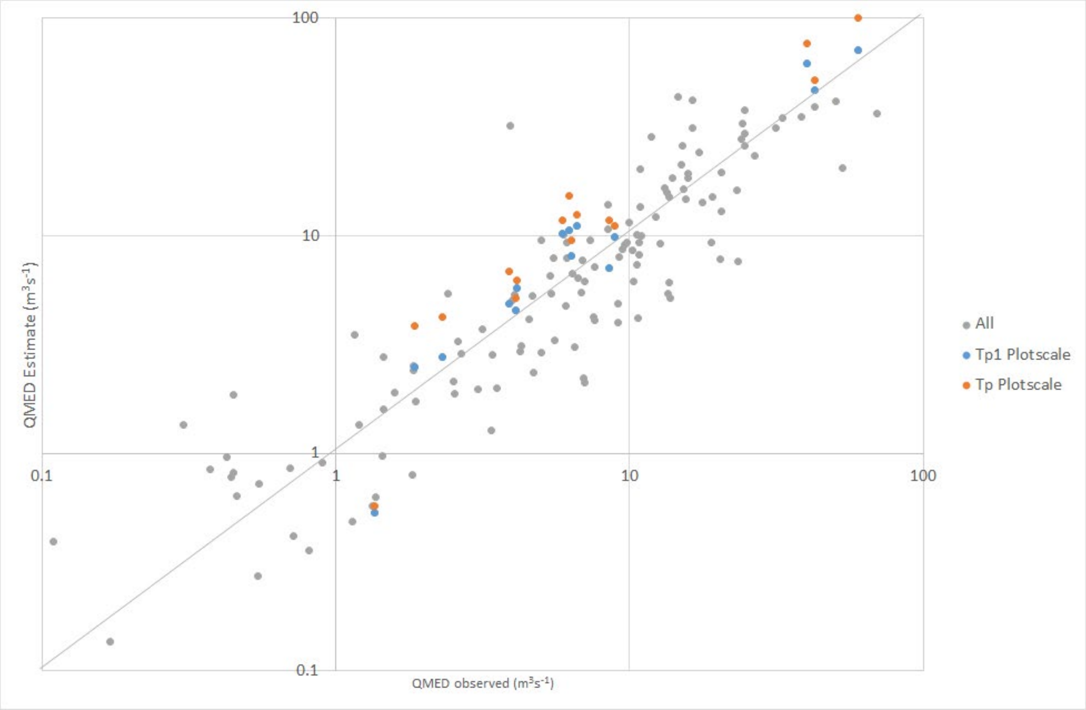


Figure 43 - The observed QMED and that estimated using the plot-scale Tp equation where Tp is limited

The y-axis of Figure 43 shows the QMED estimate (m^3s^{-1}). The x-axis shows the observed QMED (m^3s^{-1}). The small catchment data set is presented for comparison.

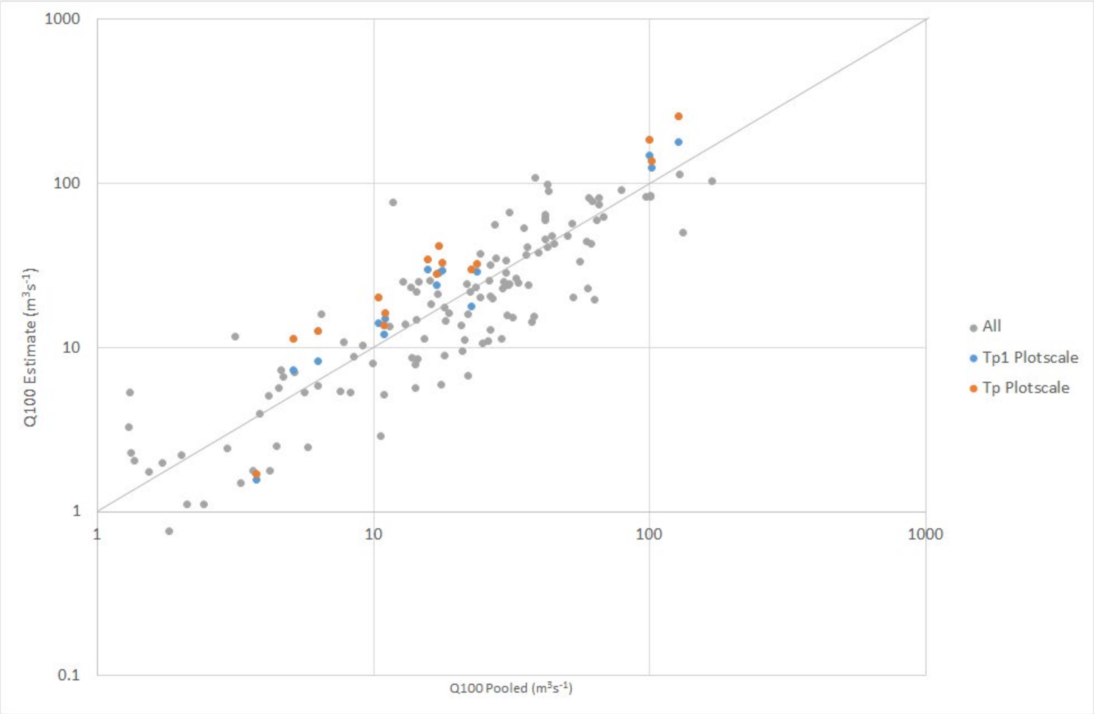


Figure 44 - The Q100 estimated using the plot-scale Tp equation and the pooled statistical estimate where Tp is limited

The y-axis of Figure 44 shows the Q100 estimate (m^3s^{-1}). The x-axis shows the Q100 pooled statistical estimate (m^3s^{-1}). The small catchment data set is presented for comparison.

Discussion

The results in Table 9 illustrate that catchments which are Tp-limited tend to be wetter (PROPWET and SAAR are higher), smaller (AREA and DPLBAR are lower) and steeper (DSPBAR is higher). Area is of least importance, with wetness and steepness dominating.

For those catchments where the Tp is initially estimated as being less than one within the small catchment data set, the results indicate that there is a tendency to overestimate the QMED and give higher estimates for Q100 than those obtained using the pooled statistical method. Limiting the Tp to 1 reduces the bias in the ReFH2 peak flow estimate for both event rarities. Where the Tp is limited, the fse and bias are generally lower when the plot-scale equations rather than the catchment-based Tp equations are used. However, the differences are marginal and based on data sets that are both small and have a marginally different membership. Therefore, this outcome should be treated with caution.

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 is used.

It is recommended that where the catchment area approaches the ‘small’ catchment definition (less than 25 km^2) the catchment Tp equation should be used where possible. For catchments close to the lower limit of 0.5 km^2, the catchment equation should be used unless there is a clear justification for adopting the plot-scale equation based on an examination of catchment descriptors (for example, unusually high or low values of DPLBAR or DPSBAR).

3.5 Plot-scale assessment of the sensitivity of greenfield peak runoff rates estimates to a bounding lower limit of Tp

This assessment is essentially a sensitivity analysis as there are no extensive plot-scale observations against which the ReFH2 estimates can be evaluated.

Within greenfield runoff rate calculations, it is currently accepted practice to estimate greenfield runoff rates for a nominal area of 50 hectares (0.5 km^2) and then linearly scale the results to the extent of development site (the plot scale).

The origins of this limit can be traced back to using the IH124 small catchment methods for greenfield runoff calculations (Environment Agency 2012) and the limitation specified within the Flood Estimation Handbook that the FEH methods should not be used for areas of less than 0.5 km^2. The FEH restriction is, however, based on a theoretical consideration of the resolution of catchment descriptors rather than hydrological considerations. Given that this limitation would apply for all catchment descriptor-based methods, then if this limit were applied literally, no methods, FEH or otherwise, should be applied in catchments or plots of less than 0.5 km^2. A better interpretation of the limit is that, as the analysis reduces to small scales, methods should be used recognising that the application is an extrapolation of both models and the underpinning catchment descriptor data sets.

However, the 0.5 km^2 limit is a convenient measure to prevent methods being applied at such a scale that the catchment area dependencies within some of the methods result in unfeasibly high runoff rates being generated. An alternative interpretation in terms of the objective of sustainable drainage is that the control of runoff is about protecting a notional downstream flood risk and a 0.5 km^2 catchment is an appropriate scale at which to assess this.

Methodology

In the absence of an equivalent plot-scale data set, a synthetic plot-scale data set was derived by setting the catchment areas for each of the small catchment data set to 50 hectares. This is a reasonable approach as the other catchment descriptors used within the plot-scale set of equations are not correlated with area over the range of catchments in the small catchment data set used. The QMED and Q100 were estimated using the plot-scale equations, generating alternative estimates with Tp set to one hour when the equation-based estimate was less than one. To assess the sensitivity of the results to the

Tp value the results were then compared for those where the Tp was limited to one hour and those where it was not. Of the 143 catchments being used from the small catchment data set, 48% had a Tp less than one hour when setting an area of 0.5 km^2.

Results

The catchment descriptors relevant to Tp are presented in Table 12. Maps of the UK indicating areas where PROPWET and SAAR exceed the minimum presented in this table where Tp is limited are shown in Figure 45. This illustrates that, in general, Tp will only tend to be limited within the wetter western side of the UK.

Table 12 - Variability of relevant catchment characteristics for cases where plot-scale Tp would be less than one based on an assumed catchment area of 0.5 km2 and all catchments under this assumption

Catchment descriptor	Plot-scale Tp-limited (mean)	Plot-scale Tp-limited (min)	Plot-scale Tp-limited (max)	All cases (mean)	All cases (min)	All cases (max)
PROPWET	0.59	0.45	0.83	0.46	0.22	0.83
SAAR	1628	1043	3473	1150	567	3473

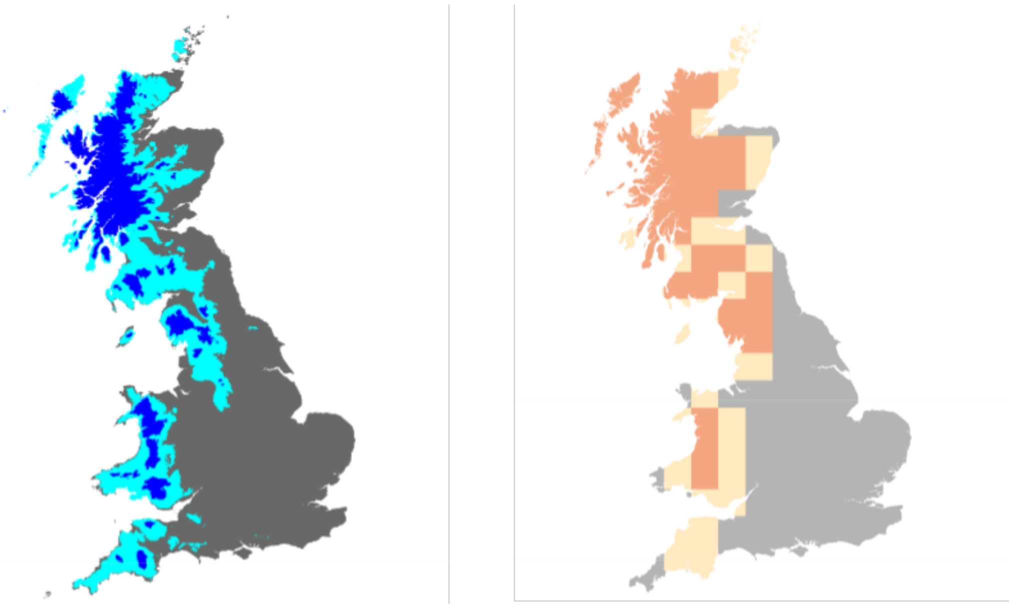


Figure 45 - Locations where the Tp estimated from the plot-scale equation may fall below one hour for a notional area of 0.5 km²: SAAR classified according to SAAR greater than 1,000 and 1,600 mm respectively (left-hand map) and PROPWET with the highlighted areas representing PROPWET greater than 0.45 and 0.6 respectively (right-hand map)

The relationships between the QMED and Q100 estimates for those catchments with Tp values of less than one hour and the equivalent estimates obtained by setting Tp to one hour are presented in Figures 46 and 47. The comparative bias is 30% and 76% for QMED and Q100 respectively, that is, the peak flow values where Tp is limited to one hour are 30% and 76% lower than the corresponding estimates when Tp is not limited and reduces below one hour.

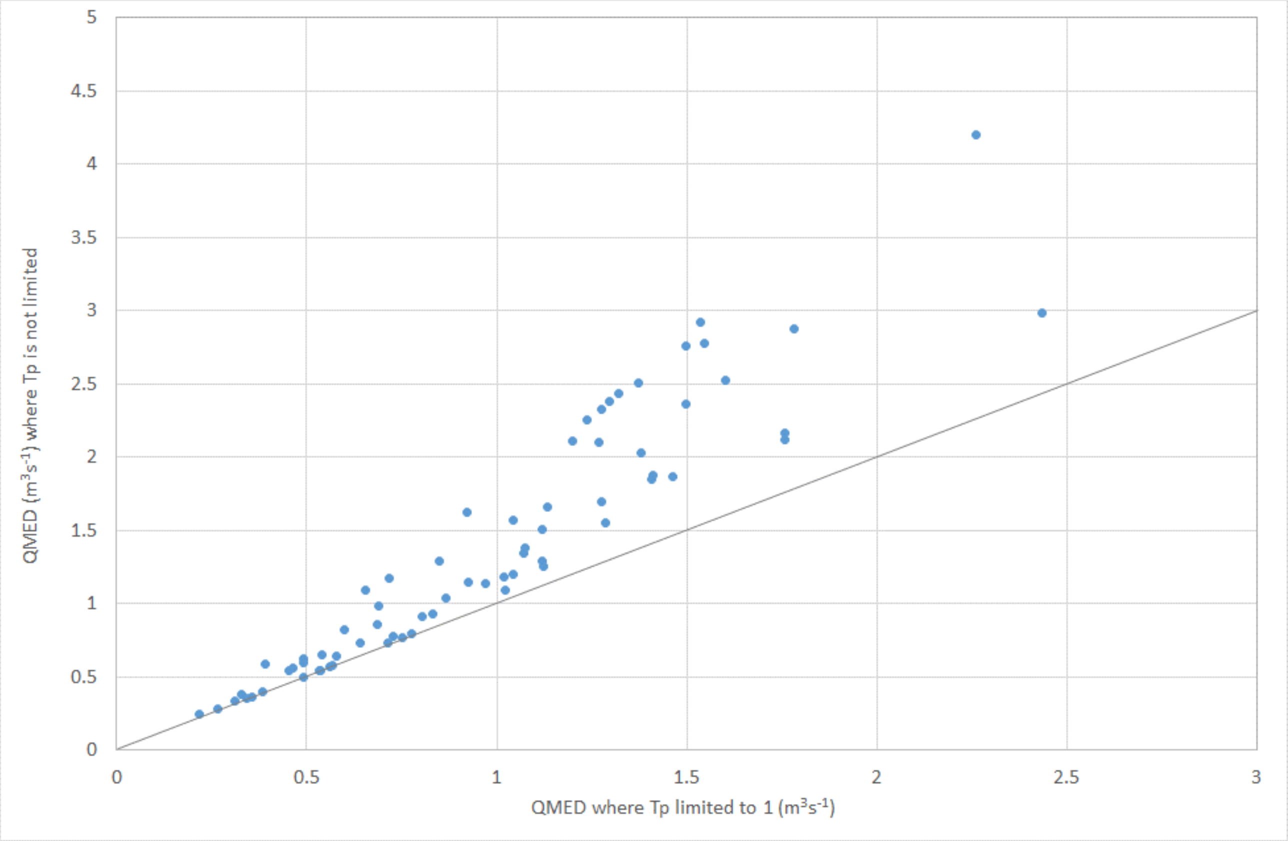


Figure 46 - Estimates of QMED comparing where Tp is, and is not, limited to 1

The scatter graph in Figure 46 plots QMED (m^3s^{-1}) where Tp is limited to 1 (x-axis – from 0 to 3) and not limited to 1 (y-axis – from 0 to 5).

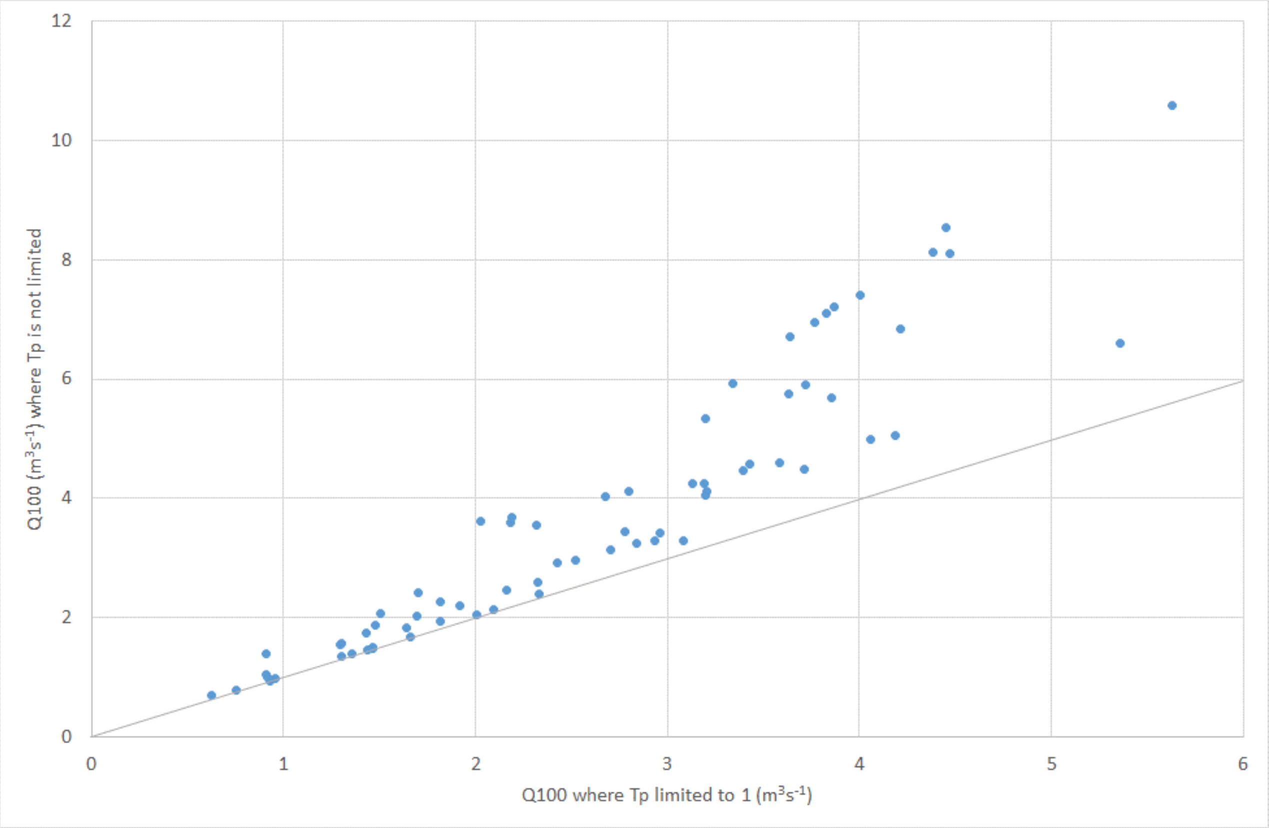


Figure 47 - Estimates of Q100 comparing where Tp is, and is not, limited to 1

The scatter graph in Figure 47 plots QMED (m^3s^{-1}) where Tp is limited to 1 (x-axis – from 0 to 6) and not limited to 1 (y-axis – from 0 to 12).

Figure 48 represents the percentage difference between the QMED peak flow estimates for the two scenarios. There is a gradual increase in the rate of percentage change in the peak flow estimate as the Tp decreases below one hour. This starts to become significant when Tp is below approximately 0.6 hours, that is, the peak flow estimate becomes very sensitive to the Tp value once this is below 0.6 hours.

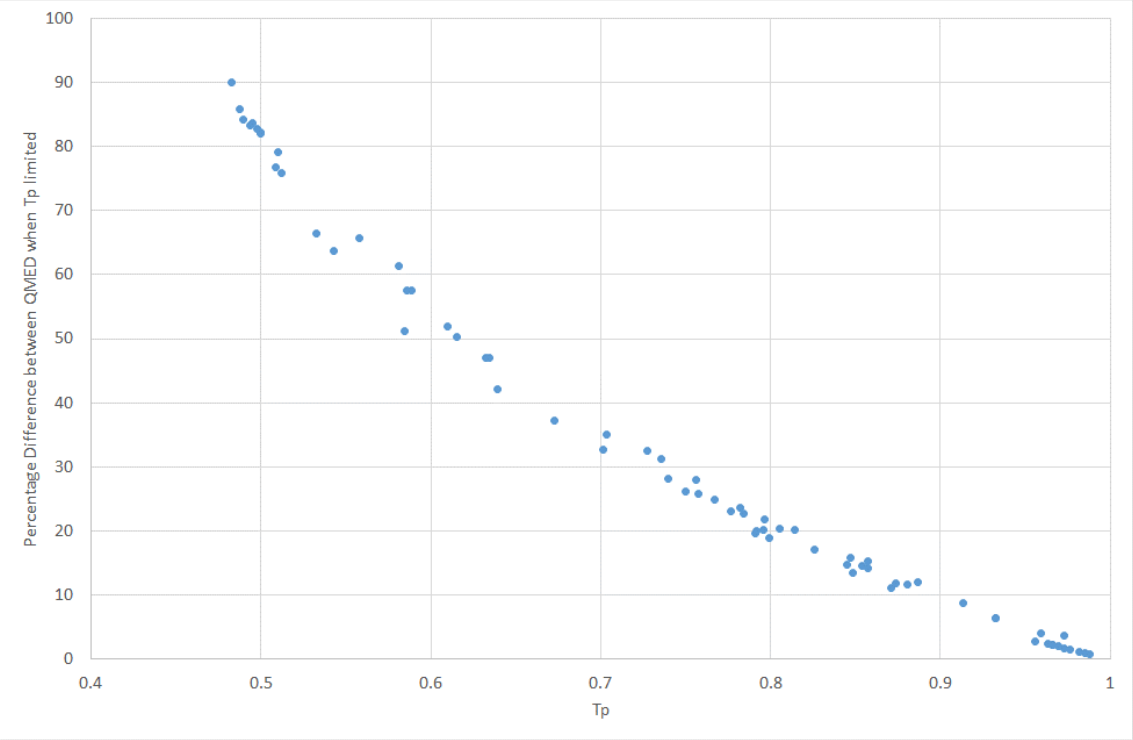


Figure 48 - Percentage difference between QMED when Tp is and is not limited to one hour plotted as a function of the unlimited, raw Tp estimate

The scatter graph in Figure 48 plots the percentage difference between QMED when Tp is limited to 1 (y-axis - 0 to 100) by the unlimited Tp estimate (x-axis - 0.4 to 1).

A comparison between the QMED calculated using the catchment descriptor equation and ReFH is presented in Figure 49. The comparative bias when the Tp is limited to 1 is -2% compared with 28% when the Tp is not limited to one hour.

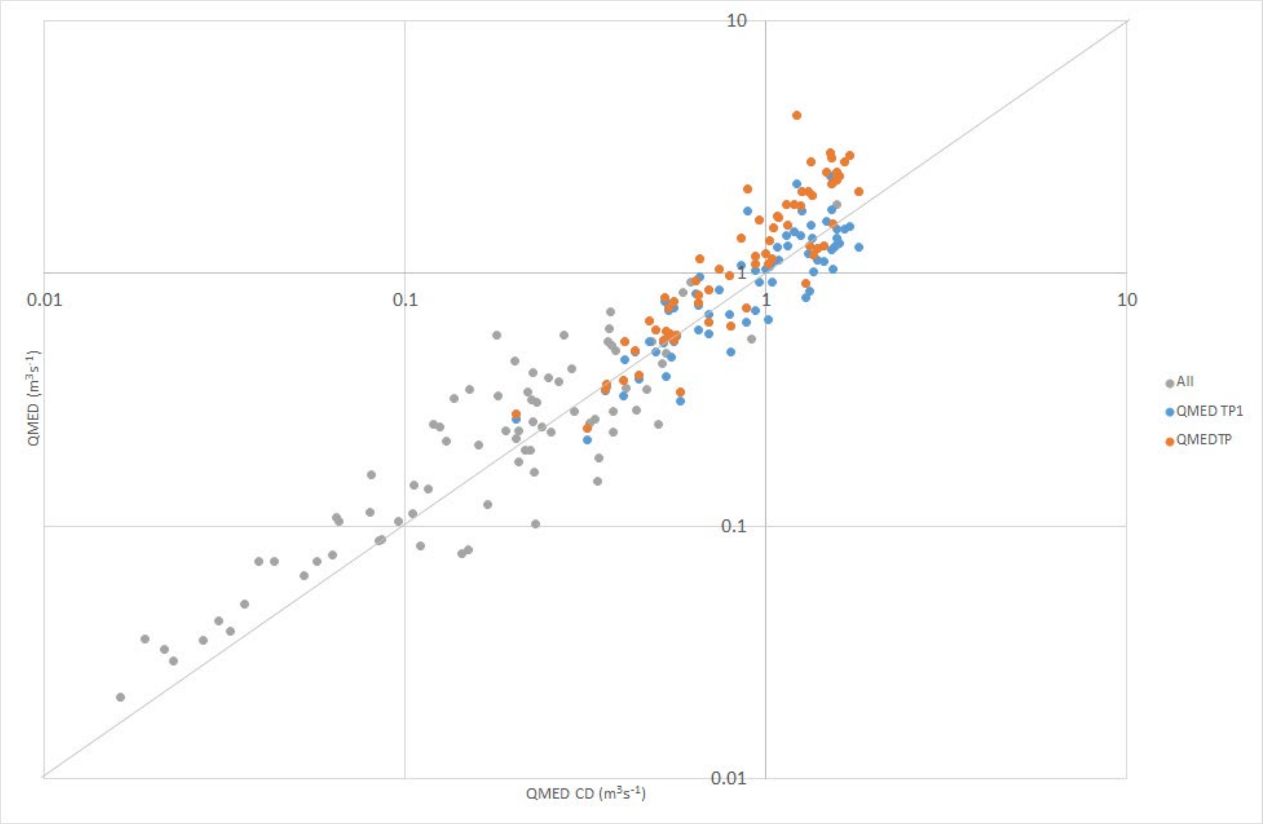


Figure 49 - QMED as estimated using ReFH2 and the catchment descriptor equation for an area of 50 hectares

The scatter graph in Figure 49 plots QMED (m^3s^{-1}) by the QMED catchment descriptor equation (m^3s^{-1}).

Discussion

These results suggest that it is appropriate to use a Tp limited to one hour when implementing the Tp plot-scale equation within ReFH2 for greenfield runoff rate calculations. Limiting Tp to one hour will provide a peak flow that is lower than if the Tp was not limited which, when used to estimate greenfield runoff rates, provides a conservative peak flow estimate (that is, the allowable rate of drainage from the site will be lower). In addition, peak flows estimated using the Tp limited to 1 are broadly in agreement with the QMED as estimated using the catchment descriptor equation, as demonstrated in Figure 49.

4 Conclusions and recommendations

4.1 Conclusions

Hydrograph shapes and time-to-peak

The Tp catchment descriptor equation can estimate values of less than one hour in small, high rainfall steep catchments. ReFH2 limits the value of Tp to one hour to reflect the model time step used in the original calibration work. This study concludes that this lower band is appropriate. Catchment in the small catchments data set with initial Tp estimates of less than 1 tend to overestimate QMED and give higher estimates for Q100 than those obtained using the pooled statistical method.

Limiting the Tp to 1 reduces the bias in the ReFH2 peak flow estimate for both event rarities. Where the Tp is limited, the fse and bias are generally lower when the plot-scale equations rather than the catchment-based Tp equations are used. 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 is used. However, the differences are marginal and based on data sets that are both small and have a marginally different membership. Therefore, this outcome should be treated with caution.

Consideration of the same issue for plot-scale application identified that the ReFH2 estimates of the 1:2 year runoff event were closer to the equivalent estimate derived using the FEH QMED catchment descriptor equation.

An evaluation of hydrograph shapes within a sample of gauged catchments has identified that the hydrograph shape predicted by ReFH2 is generally consistent with the shape of observed events, particularly in rural catchments. The analysis considered the shape of normalised hydrographs and not volume which is an important distinction.

It remains difficult to characterise typical normalised hydrograph shapes in highly urbanised and/or groundwater-dominated small catchments using any methods. Caution should be exercised in these catchments when the shape of the hydrograph, over and above the estimation of event volume is important.

Flood seasonality and the influence of urbanisation on seasonality

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 ($URBEXT_{2000} < 0.15$) for all catchment types.

Considering the ‘very heavily urbanised’ class ($URBEXT_{2000} \geq 0.30$) summer storms dominate the flood regime of catchments in this class.

Within the $0.15 \leq URBEXT_{2000} < 0.30$ interval, if the SAAR value is less than 800 mm and the catchment is permeable ($BFIHOST \geq 0.65$), then there is some evidence to suggest that summer floods may dominate, otherwise the dominant flood season is still winter.

A new equation for estimating the summer C_{ini} has been developed and the revised recommendations for when a summer storm should be used in urban catchments have been proposed.

4.2 Recommendations

Seasonality

The choice of summer or winter storm in ReFH2 depends upon 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 $BFIHOST \geq 0.65$ 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

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 to 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.

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 for catchments with $URBEXT_{2000} < 0.3$ 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, the urbanisation model can be applied for lower levels of urbanisation, recognising this may provide a precautionary estimate of peak flow and direct runoff volume. A Tp factor of 1 and a default IF of 0.3 should be used, regardless of the value of BFIHOST or of the chosen storm seasonality. The IF can be revised based on detailed mapping.

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 possible, except in catchments where the value of either DPLBAR or DPSBAR is an outlier relative to UK catchments, for example, where the catchment is an elongated valley with little contributing area above the head of the valley.

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List of abbreviations

BFIHOST	Base flow index derived from HOST classification
CEH	Centre for Ecology & Hydrology
C_{ini}	Initial soil moisture content (mm)
C_{max}	Maximum soil moisture content (mm)
DPLBAR	Catchment mean drainage path length (km)
DPSBAR	Catchment mean drainage path slope (m/km)
HWA	Hydrograph width analysis (software)
DOE	Duration of exceedance
EMH	Empirical method hydrograph
FEH	Flood Estimation Handbook (IH 1999)
FEH13	FEH13 rainfall depth-duration-frequency model
FSR	Flood Studies Report (NERC 1975)
FSU	Flood Studies Update
PDM	Probability distributed model
PROPWET	Index of proportion of time that soils are wet
QMED	Median annual maximum flood
ReFH, ReFH2	Revitalised flood hydrograph model/design package
SAAR	Standard period average annual rainfall (mm)
SCF	Seasonal correction factor
Tp	Time-to-peak of unit hydrograph (h)
$URBEXT_{2000}$	FEH index of fractional urban extent based on LCM2000

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