Estimating flood peaks and hydrographs for small catchments:

R7 – Investigations of plot-scale runoff data

FCERM Research & Development Programme

Research Report

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Email: fcerm.evidence@environment-agency.gov.uk.

Author(s):
Duncan Faulkner, Lisa Stewart, Andy Young

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Research contractor:
Centre for Ecology & Hydrology, Wallingford, Oxfordshire, OX10 8BB, 01491 838800.

Environment Agency's Project Manager:
Mark Whitling

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Independent consultant

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Alexander Siddaway

Wallingford HydroSolutions

Andy Young

Tracey Haxton

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Executive summary

This report describes analyses carried out during the early part of project SC090031 ‘Estimating flood peaks and hydrographs in small catchments (Phase 2)’. It is important to note that in the intervening period considerable modifications have been made to the FEH design event (ReFH) method and the ReFH1 method has been superseded by ReFH2. The analyses reported involve applying different variants of FEH methods to data from three small plots (two at North Wyke in Devon and one at Pontbren in mid Wales). The study has focused on estimating QMED, the median annual maximum flow, since the available streamflow records were not long enough to support the investigation of more extreme flood events.

The core of the analysis has been to evaluate whether the existing FEH methods are suitable to apply at the plot scale, given that dominant hydrological processes can vary greatly between hillslope or plot scale and catchment scale. The results provide some limited evidence to suggest that methods based on the plot scale (that is, where catchment descriptors have been adjusted or QMED estimated directly from Peaks over Threshold (POT) data at the plot scale) may produce higher estimates of QMED than methods based on scaling results from larger catchments. This finding has different implications depending on whether the purpose of the exercise is to estimate the runoff at the outlet of the plot or the contribution of the plot to downstream flood risk. In either case, it is important to consider the hydrological characteristics of both plot and downstream catchment.

Since the original analysis of the performance of ReFH1 using the plot-scale data, the ReFH2 method has been released. ReFH2 addresses some of the concerns referred to above by providing an option for estimating parameters using catchment descriptors that do not depend on the presence of a stream network. An evaluation of the first version of ReFH2 using the FEH99 rainfall demonstrates that the modelling framework is broadly appropriate for simulating runoff generation in the relative impermeable plots for which data were available. It is recommended that the value of time-to-peak, T_p, in the ReFH2 design package should be constrained to a lower limit of one hour.

Important Note:

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

1. Introduction

There is a large demand for estimates of greenfield runoff data from plots, that is, runoff that has not yet entered a watercourse, and yet these estimates are usually made using methods that were developed from stream flow measurements at the small catchment scale rather than runoff measurements at the plot scale. Most gauged small catchments are larger than 1 km^2, whereas many development sites are under one hectare, that is, at least 100 times smaller. Even if an area does not appear to yield local surface runoff, it does not mean that it is not contributing to storm flow in the stream network further downstream. Appendix B of the phase 1 report for the current project (Environment Agency, 2012) considered in more detail the translation of flows from catchment scale to plot scale. It pointed out the importance of considering the motivation for estimating plot-scale runoff, making a distinction between the purposes of limiting contributions to downstream flood risk (at the catchment scale) and limiting local surface water flooding (at the plot scale). The approach of scaling down peak flows by area was investigated, considering an apparent trend towards greater linearity between peak flow and area for the smallest catchments. The phase 1 report concluded that “with the true source of observed streamflow undefined, and with the changing balance between in-field and in-channel processes, the extrapolation of flood estimation across catchment scales is uncertain.”

Potential sources of plot-scale runoff data were listed in the phase 1 report, and data from two sources were provided: the Pontbren experimental catchment in Wales and the North Wyke facility in Devon.

During phase 2 of this project additional sources of experimental runoff data sets were pursued to investigate whether the changing balance of the key hydrological processes with scale invalidates current design methods. Unfortunately, it was not possible to extend the sources of suitable data and therefore the analysis presented within this report is restricted to an analysis of the Pontbren and North Wyke data sets.

The core of the analysis has been to evaluate whether the structure and parameters of the ReFH model are suitable for applying at the plot scale, given that dominant hydrological processes can vary greatly between hillslope or plot scale and catchment scale. Since then, development of the ReFH2 method outside the current project has addressed some of these concerns by providing an option for estimating parameters using catchment descriptors that do not depend on the presence of a stream network. An evaluation of the first version of ReFH2 using the FEH99 rainfall model has been included in the analysis (Section 8).

2. Review and selection of field measurement sites

There is little systematic measurement of runoff before it is concentrated in watercourses, perhaps unsurprisingly given the difficulties involved (described in the introduction to Beven, 2012) and the spatially distributed nature of the phenomenon, meaning that the runoff in any particular location is unlikely to result in any great flood risk, or have any significant value in terms of water resources. The relatively few data sets that directly measure surface runoff tend to be from experimental studies of limited spatial extent and duration such as those reported by Whipkey (1965), Dunne and Black (1970), Marshall and others (2009) and Rodda and Hawkins (2012) or, in urban areas, from sewer modelling studies. Many references describe runoff measurements during a small number of events, rather than continuously. There are also numerous references to measurement of runoff from artificial rainfall created by sprinklers. Such data was not considered suitable for the present investigation.

Runoff data was sought from several sources, but only a small number of suitable data sets were obtained. These were from North Wyke (2 plots) and Pontbren sites presented in the phase 1 report.

Other sources investigated were:

ADAS: Runoff data are available for several plots up to six ha. For most plots, only tile drain discharge is monitored rather than total runoff. There are some limited data on surface runoff from drained plots but this was collected with the main objective of quantifying concentrations in the runoff rather than measuring runoff per se, and ADAS advised that it is possible not all the runoff was captured. ADAS also holds streamflow data for several small catchments, ranging in area from 30 ha up to around 1 km^2, some of which were used in the development of IH124 (for example, Cliftonthorpe, Lower Smithy, North Weald and Redesdale). No data was obtained from ADAS due to the limitations noted above and the costs associated with acquiring the data sets.

United Utilities, SCaMP (Sustainable Catchment Management Plan) programme: Streamflow data are available from six small catchments or plots in the Forest of Bowland, Lancashire. The flow measurements were made by Penny Anderson Associates for a period of around five years. The data were provided by United Utilities but did not include any plot-scale runoff measurements.

Environment Agency Project SC060092 – 'Multiscale experimentation, monitoring and analysis of long-term land use changes and flood risk': This project covered the same area as the SCaMP project, in the Forest of Bowland, but flows were measured at different locations, for a period of three years starting in early 2008. A paper on this project (O'Donnell and others, 2008) describes monitoring of flow from very small areas, down to hundreds of square metres. The project data set did include measurements of water level from areas down to ‘less than 0.4 km^2’ but it was not clear that these represented plot-scale measurements, and, in any event, no rating curves were available.

Universities of Durham and Leeds and CEH Lancaster Environment Centre, Moor House research site, Upper Teesdale: Flow was measured on four very small catchments in the 1950s to 1960s as part of an investigation of the impact of artificial drainage on peatland catchments (Conway and Millar 1960). More recently, the University of Leeds has measured runoff at the plot scale from 2002 to 2004 (Holden and others, 2006) and the University of Durham is currently monitoring other plots. There are large gaps in recent data due to the failure of the equipment during most winters, so it is unlikely that the data will be useful for constructing a flood peak series. This upland peatland area is not typical of the locations where most small catchment design flows are needed and so it was decided not to incorporate any runoff data from Moor House in the study.

University of Exeter: runoff data was sought but nothing suitable was found.

In addition to the above, data were sought from local authorities and water companies and via a general appeal in a webinar, but no suitable flow data sets were found.

The North Wyke site, located on Rowden Moor near the River Taw in Devon, includes 12 lysimeter plots, each around one ha, along with two slightly smaller plots (Rodda and Hawkins, 2012). Each lysimeter plot is bounded by gravel interceptors to isolate overland surface runoff and surface lateral flow (to 0.3 m depth) so that the plot is hydrologically isolated from its neighbours. Seven of the lysimeters are also drained to 0.85 m depth by tile drains at 40 m intervals across the slope, overlain by mole drains at 2 m spacing and a depth of 0.55 m down the slope. Runoff data was provided by Rothamsted Research for two plots, one drained (plot 4) and one un-drained (plot 8). Data from other plots may exist but have not been made available.

The Pontbren plot is located in mid Wales in the headwaters of the Severn catchment, an upland area with sheep farming (Marshall and others, 2009). A multi-scale catchment experimental programme was set up at Pontbren as part of the UK Flood Risk Management Research Consortium, with the aim of bridging the gap between plot-scale experiments and assessment of catchment-scale impacts. Runoff was measured at a small hillslope which drains via a field drain with a contributing area of 0.36 ha and via overland flow from an area of 0.44 ha. Both drain flow and overland flow were monitored, the latter by means of a gutter inserted into the ground. Stream flow was measured at various locations across the catchment. Data from Pontbren were provided by Imperial College.

The details of the plots are outlined in Table 1 and the locations of the sites are shown in Figure 1.

Table 1 - Plot-scale runoff site details

Details	Pontbren	North Wyke Plot 4	North Wyke Plot 8
Grid reference	SJ 05400 06150	SX 65000 99500	SX 65000 99500
Drainage	Drained	Drained	Un-drained
Area (ha)	0.44	1.03	1.02
Elevation (m)	310	150	150
Slope	12%	5-10%	5-10%
Soil type	Clay – Cegin series	Clay - Hallsworth series	Clay - Hallsworth series

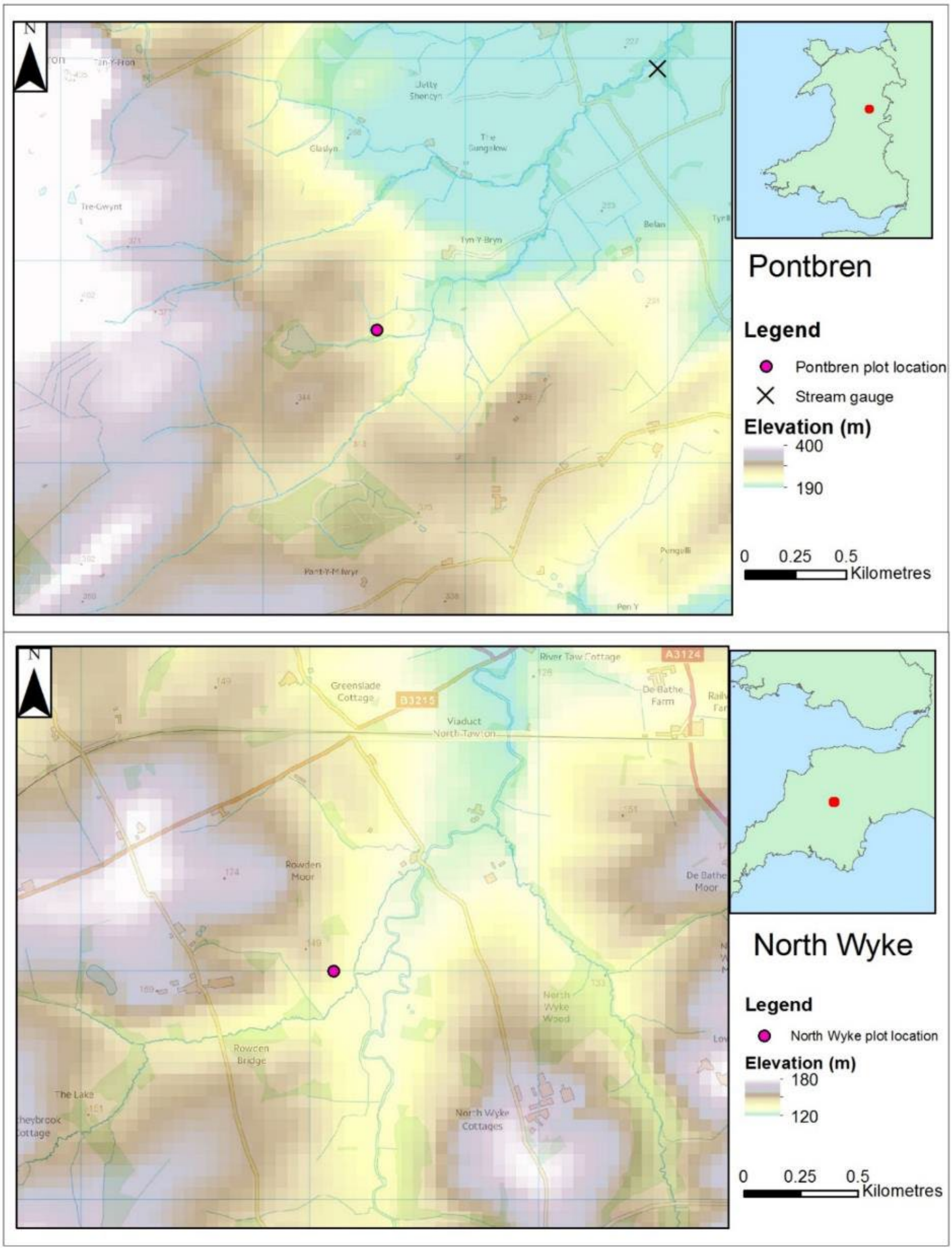


Figure 1 - Plot-scale runoff sites

The maps in Figure 1 show the plot-scale runoff sites: Pontbren (top map) and North Wyke (bottom map). The maps show the elevation in metres ranging from 120 metres (light green) to 180 metres (white) and the runoff site is plotted with a red circle on each map. The scale of the maps is 0.5 km: 3 cm.

3. Available data and evaluation methodology

For each of the three plots considered in the analysis, the aim was to estimate the median annual maximum flood (QMED) using both gauged data from the plots and area-adjusted FEH methods (statistical and ReFH) applied at the catchment scale. The focus on QMED resulted from flow data records which were not long enough to consider longer return periods. Additionally, event response was studied, examining the difference in peak flows between the gauged plots and gauged downstream catchments. The available data at each plot largely determined the methods chosen to estimate QMED.

Table 2 outlines the data required for each method of analysis.

Table 2 - Data availability and method selection

Data	Estimation of QMED from ReFH with parameters from catchment descriptors	Estimation of QMED from ReFH with parameters from local data	Estimation of QMED from peaks-over-threshold data	Estimation of QMED from catchment descriptors	Analysis of individual events
Gauged flow – plot	N	Y	Y	N	Y
Gauged flow – downstream catchment	N	N	N	N	Y
Rainfall	N	Y	N	N	N
Estimated catchment descriptors	Y	Y	N	Y	N

3.1 Flow data

Plot flow

Flow data were available at North Wyke at a 15-minute temporal resolution in units of millimetres per minute. These values were then converted to litres per second, a more appropriate measure of plot scale runoff. At Pontbren, hourly flow data in litres per second were available.

The flow data records for each plot are summarised in Figures 2, 3 and 4, demonstrating record length and completeness.

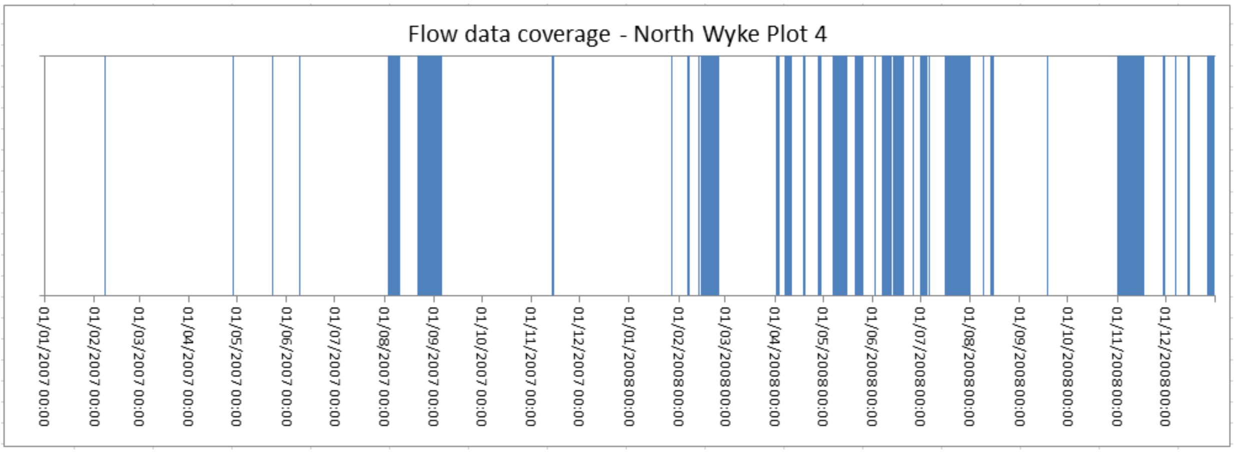


Figure 2 - Flow data coverage - North Wyke (plot 4)

Figure 2 plots the flow data records for North Wyke (plot 4) from 1 January 2007 to 1 December 2008. Blue bars indicate absent data.

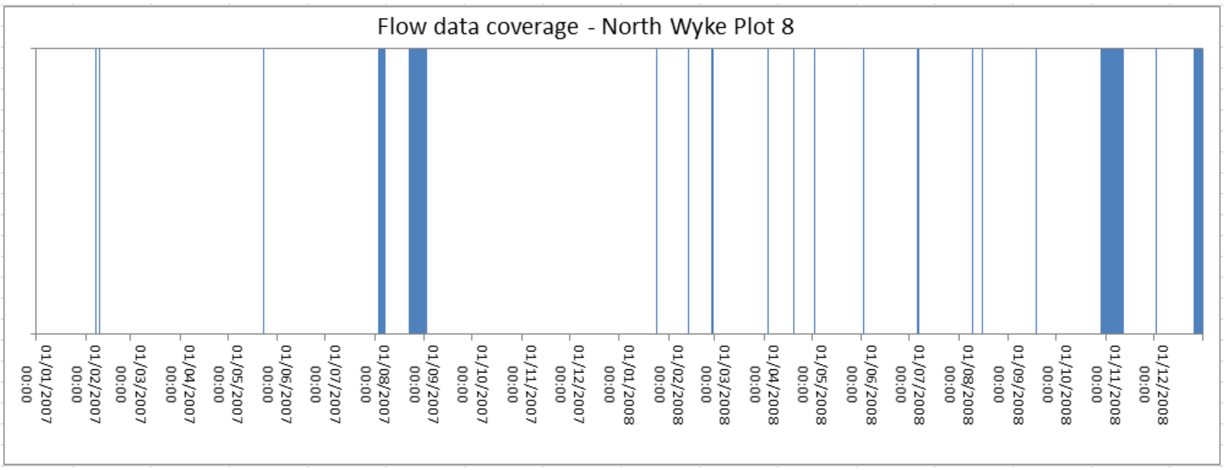


Figure 3 - Flow data coverage - North Wyke (plot 8)

Figure 3 plots the flow data records for North Wyke (plot 8) from 1 January 2007 to 1 December 2009. Blue bars indicate absent data.

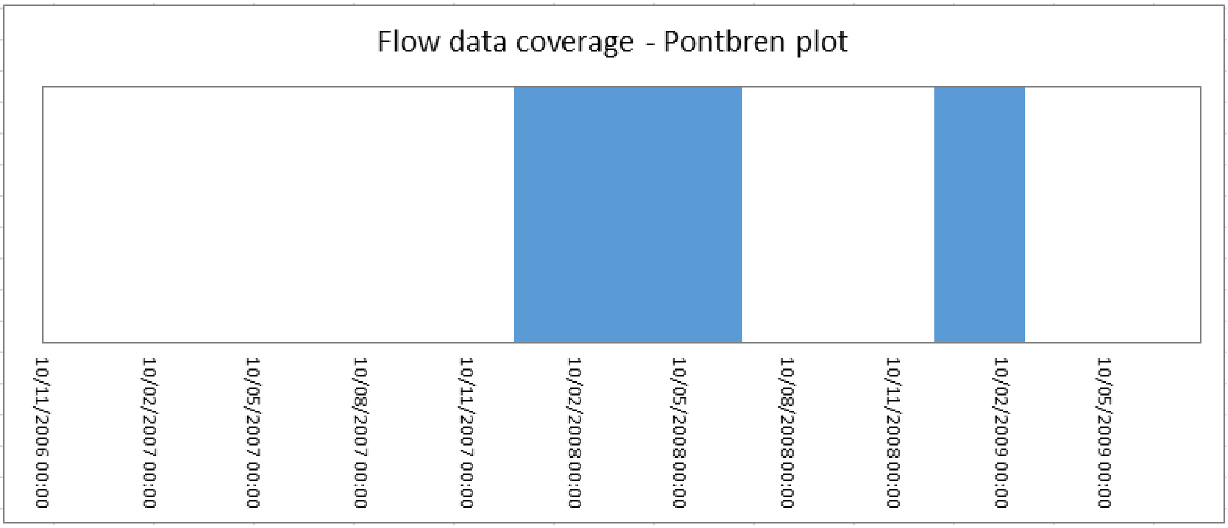


Figure 4 - Flow data coverage – Pontbren

Figure 4 plots the flow data records for the Pontbren plot from 1 November 2006 to 10 May 2009. Blue bars indicate absent data.

QMED estimates using POT data rely on at least two full years of complete data. The length of flow record was marginal for both sites, being exactly two years at North Wyke and approximately 33 months at Pontbren. However, both data records were broken, with significant gaps (especially at Pontbren in winter) likely to create bias in QMED values through large events being absent. Data was missing for 20% of the period at Pontbren.

At North Wyke, before around September 2006, runoff data was available only at a daily resolution (Rodda and Hawkins, 2012). Data for the period since 2008 may exist but it has not been provided.

Downstream catchment flow data

Gauged flow data was available for the gauge 6 site downstream of the Pontbren plot, draining a catchment of 3.17 km^2. The location of the gauge is shown on Figure 1. This allowed event hydrographs to be compared between the catchment scale and the plot scale. The data coverage at the gauge 6 site is presented in Figure 5.

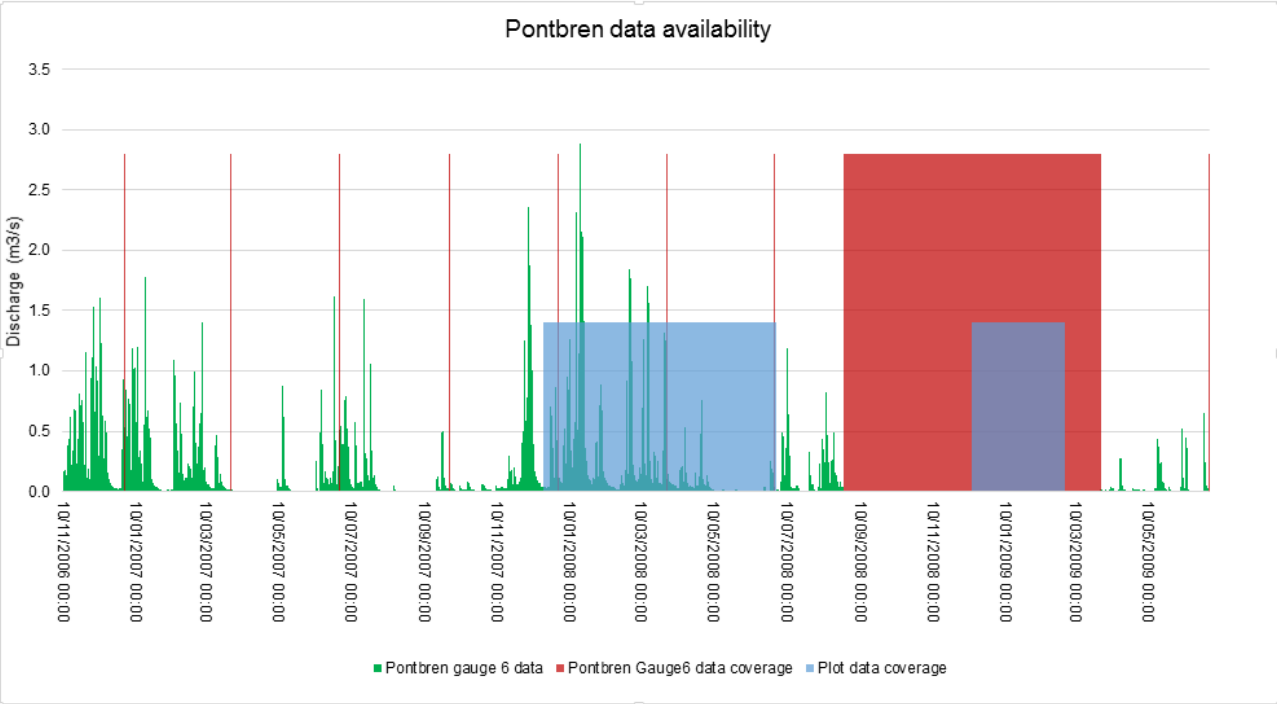


Figure 5 - Flow data coverage - Pontbren Gauge 6

The graph in Figure 5 shows the flow data coverage for gauge 6 at Pontbren. Pontbren gauge 6 data is shown in green, the data coverage at gauge 6 is shown in red, and the plot data coverage is shown in blue. Data is plotted from 10 November 2006 to 10 May 2009 (on the x-axis). The y-axis shows the discharge in m^3/s from 0.0 to 3.5. Red or blue bars indicate absent data.

Given the periods of missing data at the Pontbren plot, and the implications of estimating QMED with an incomplete period of record, examining the gauge 6 flow data can provide useful information about whether significant flood peaks have been missed from the plot. The first period of missing data at the plot (blue) coincides with several significant flood peaks at the downstream gauge, including the largest peak. This is discussed further in Section 6.2.

No suitable downstream gauge was identified for North Wyke, meaning no similar analysis was possible. The closest downstream gauge accounted for an area of 451 km^2, which was deemed too large to compare with the plot scale.

3.2 Rainfall data

Rainfall data for both sites was obtained. Natural Resources Wales provided data from the Cefn Coch rain gauge near Pontbren at a 15-minute interval. Rothamsted Research provided hourly rainfall data from the North Wyke Automatic Weather Station (AWS), Rowden AWS and RG12_13 rain gauge. The cumulative rainfall plots for each gauge at North Wyke are presented in Figure 6.

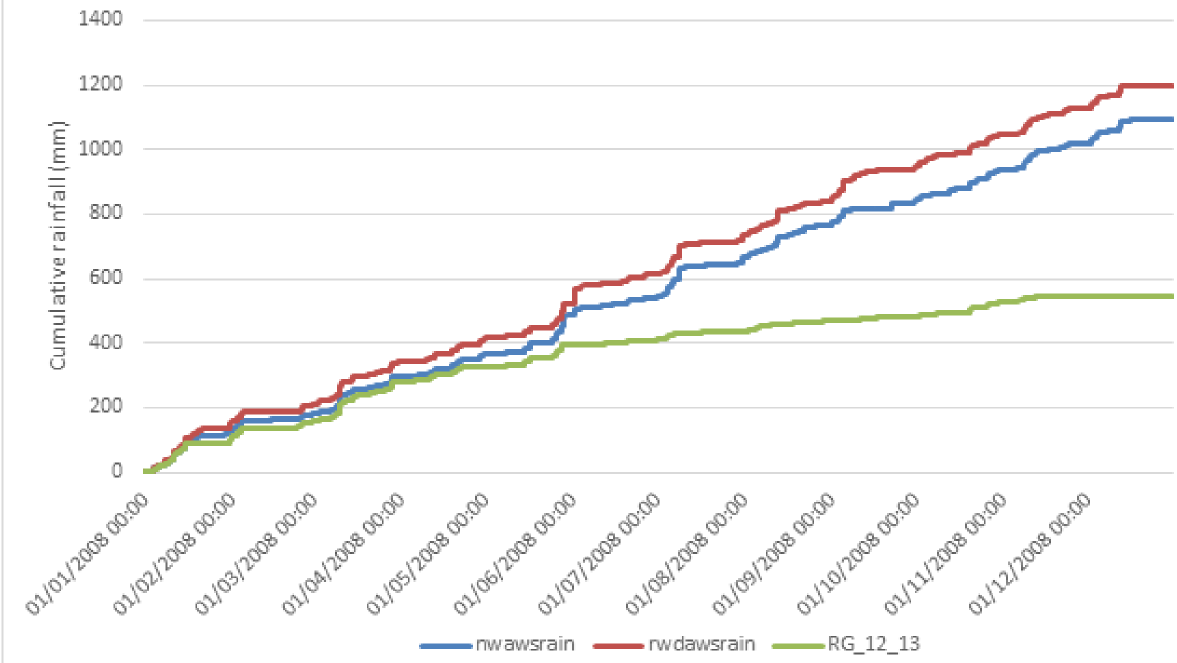


Figure 6 - Rain gauge comparison - North Wyke

The line graph in Figure 6 shows the cumulative rainfall plots for each gauge at North Wyke. The blue line plots nwawsrain, the red line plots rwdawsrain, and the green line plots RG_12_13. Data is plotted from 1 January 2008 to 1 December 2008 (on the x-axis). The y-axis shows the cumulative rainfall (from 0 to 1400 mm).

The North Wyke AWS was chosen as the rain gauge to use for the calibrated ReFH method. RG_12_13 was discounted because of its low cumulative rainfall from June 2008 onwards. Rowden AWS was considered to use in analysis but data quality for some key rainfall events was questioned.

Table 3 demonstrates that the data available for this study facilitated a broad range of QMED estimates to be derived, as well as event hydrograph analysis at Pontbren. However, as discussed in Section 3.1, estimating QMED using peaks-over-threshold data was compromised by the length and completeness of the plot flow data records.

Table 3 - Methods of analysis by site

Data	Estimation of QMED from ReFH with parameters from catchment descriptors	Estimation of QMED from ReFH with parameters from local data	Estimation of QMED from peaks-over-threshold data	Estimation of QMED from catchment descriptors	Analysis of individual events
North Wyke	Y	Y	Y	Y	N
Pontbren	Y	Y	Y	Y	Y

4. Event hydrograph analysis

The relationship between event response in the observed plot data and area-adjusted gauged downstream data was explored for Pontbren. By analysing the full event hydrograph, further inferences were made about catchment response, including peak flow comparison and rate of response. This analysis could not be carried out at North Wyke due to a lack of suitable downstream gauged data. The results for Pontbren are presented in Figures 7, 8 and 9 (these are taken from this project's phase 1 report).

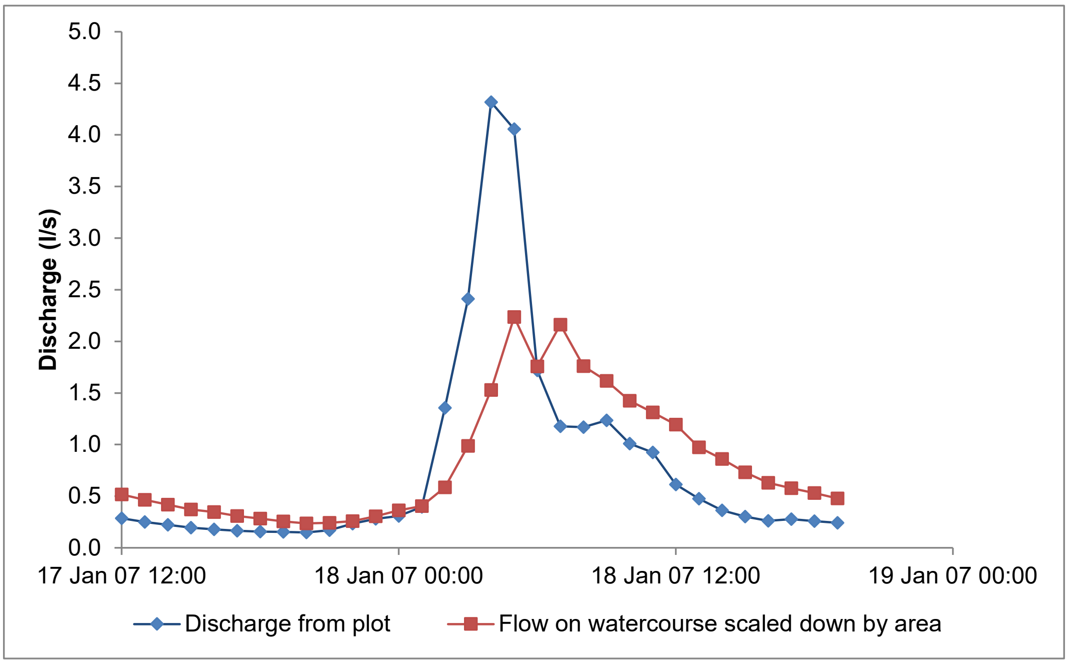


Figure 7 - Event hydrograph analysis - Pontbren (17-19 January 2007)

The line graph in Figure 7 plots the discharge from the plot (blue line) and the flow on the watercourse scaled down by area (red line). Data is plotted from midday on 17 January 2007 to midnight on 19 January 2007 (on the x-axis). The y-axis shows the discharge from 0.0 to 5.0 l/s.

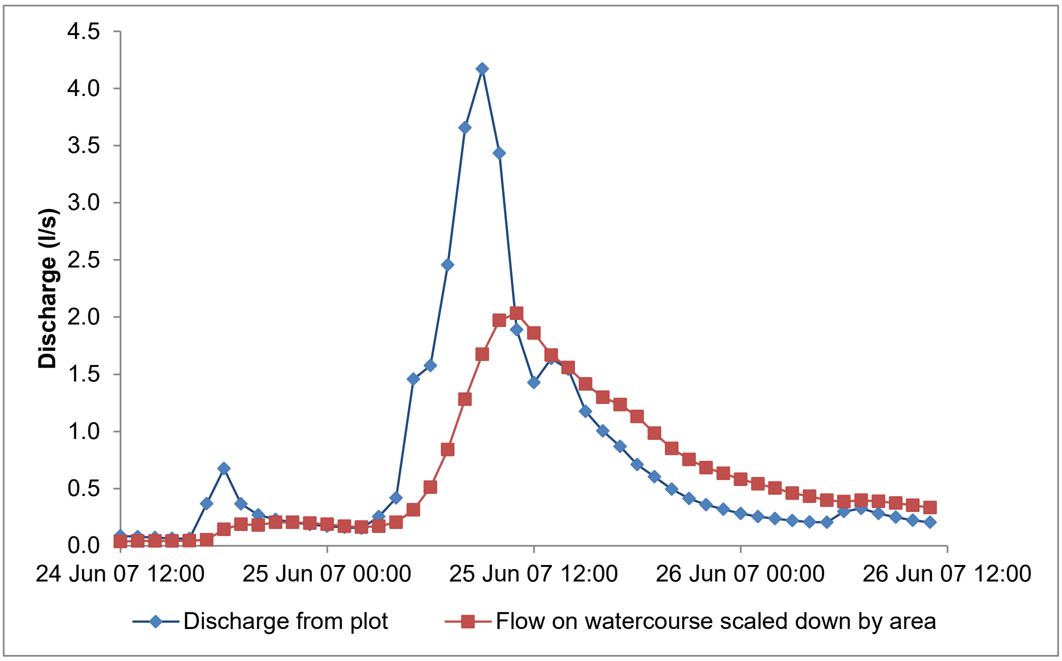


Figure 8 - Event hydrograph analysis - Pontbren (24-26 June 2007)

The line graph in Figure 8 plots the discharge from the plot (blue line) and the flow on the watercourse scaled down by area (blue line). Data is plotted from midday on 24 June 2007 to midday on 26 June 2007 (on the x-axis). The y-axis shows the discharge from 0.0 to 4.5 l/s.

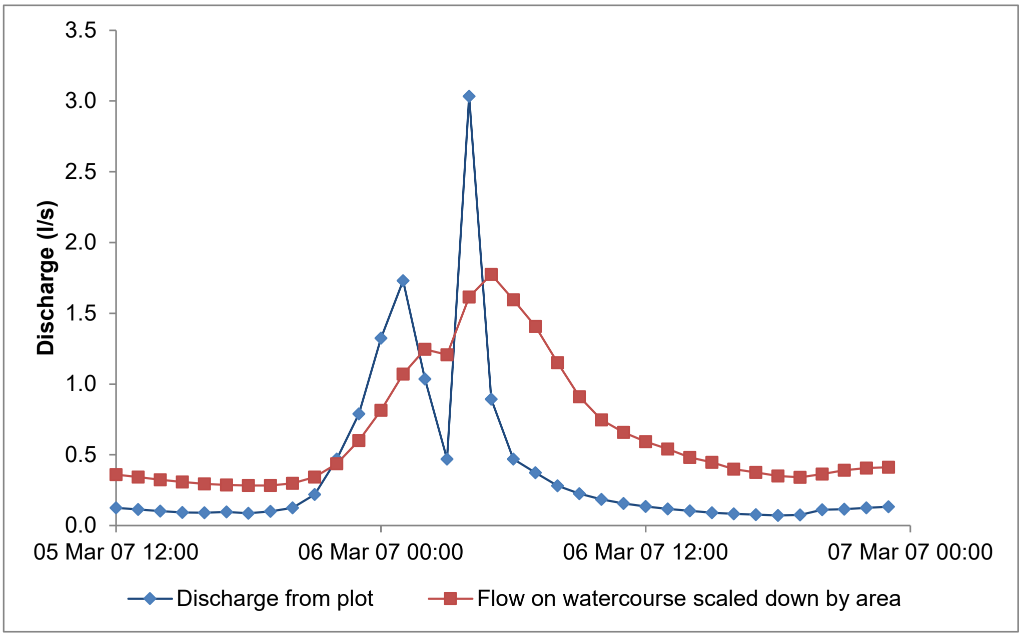


Figure 9 - Event hydrograph analysis - Pontbren (5-7 May 2007)

The line graph in Figure 9 plots the discharge from the plot (blue line) and the flow on the watercourse scaled down by area (red line). Data is plotted from midday on 5 March 2007 to midnight on 7 March 2007 (on the x-axis). The y-axis shows the discharge from 0.0 to 3.5 l/s.

The three events analysed in Figures 7, 8 and 9 demonstrate that, while the volume of runoff is comparable, the scaled hydrographs from the downstream watercourse significantly underrepresent the plot-scale peak runoff. This could be due to attenuation of peak flows, but another possible explanation is the heterogeneity in catchment properties and, therefore, runoff processes. For example, the gradient of the hill slope where plot runoff was measured is more than twice as steep as the catchment as a whole.

5. Applying the original ReFH method (ReFH1)

The ReFH rainfall-runoff model was developed to model flood hydrographs on rivers. It does not necessarily apply to representing of runoff from plots, where some of the flow processes that affect stream flow (for example, channel and flood plain attenuation or contributions from base flow) do not apply. Applying the original ReFH method is complicated by the fact that some of the catchment descriptors relate to drainage geometry, which may not be relevant to a plot scale. Furthermore, catchment descriptors are only available for complete catchments, so for plots that are not complete catchments, descriptors have to be estimated through disaggregation – essentially identifying a complete catchment enclosing the plot, removing smaller complete catchments from this until only the plot remains, identifying descriptors for each catchment, and combining these to estimate descriptors that are appropriate for the plot area. Within the ReFH2 methodology, and with the advent of the FEH Web Service, there is a set of plot-scale equations that can be applied using point value descriptors that are directly extracted for the development site.

The smallest catchment used in developing the ReFH method was 3.46km^2, and therefore the method is not calibrated to the plot scale. This is common with most of the methods used for estimating plot scale runoff. However, one of the strengths of the method is its ability to estimate model parameters using observed data. This may be useful in attempting to replicate plot scale runoff processes to estimate QMED. The poor continuity of flow data records again proved problematic, as large events were potentially missed from the event sets.

The purpose of applying ReFH in this investigation was to investigate how accurately it was able to estimate QMED at the plot scale, using a range of approaches to estimate model parameters.

The process followed to estimate QMED using the ReFH method was to generate a 2-year return period design flow estimate using design rainfall. The four model parameters: time-to-peak (T_p), maximum soil moisture capacity (C_{max}), base flow lag-time (BL) and base flow recession (BR), were estimated either from catchment descriptors or from observed rainfall-runoff response. It should be noted that throughout the main ReFH 2-year design runs the ReFH recommended design storm duration derived from Tp and annual average rainfall was used.

5.1 ReFH1 scenarios

Several approaches (scenarios) were used to produce a range of QMED estimates for both North Wyke and Pontbren.

The first approach was to estimate ReFH model parameters from the plot-scale runoff data, therefore applying the method directly at the plot scale. This approach has been termed the ‘calibrated scenario’. Since catchment descriptors cannot be extracted at the plot scale from the FEH CD-ROM, two different approaches were followed when applying ReFH without calibration, that is, estimating model parameters from catchment descriptors. The first was to run ReFH for a small catchment and scale the result by area. The second was to estimate catchment descriptors for the plot.

At Pontbren, the downstream gauge (Pontbren gauge 6) provided an ideal catchment from which to scale ReFH results to the plot scale, constituting the first uncalibrated scenario. The second uncalibrated scenario involved adjusting the FEH catchment descriptors AREA and DPLBAR to represent the plot scale. DPLBAR was adjusted to represent the shorter average drainage path length associated with a plot scale catchment using the equation given in volume 5 of the Flood Estimation Handbook (FEH) and shown in Equation 1:

Equation 1 – Relationship between FEH catchment descriptors DPLBAR and AREA (from Bayliss, 1999)

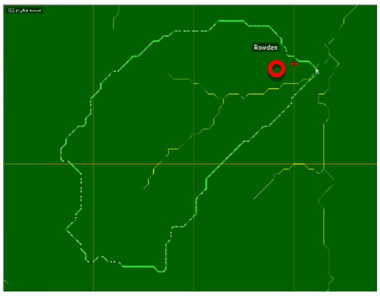
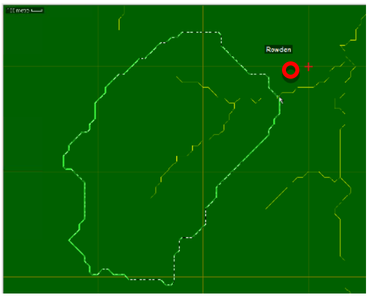
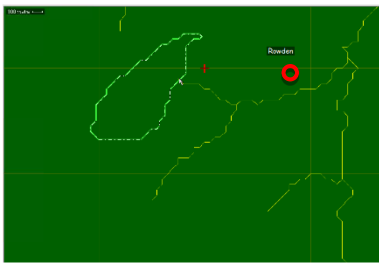
$$DPLBAR = AREA^{0.548}$$

Other descriptors, such as those representing climatic and soil properties, were assumed to be identical at the plot scale as at the downstream catchment scale, given the lack of high-resolution FEH catchment descriptors to enable estimation at the plot scale. This is likely to be a reasonable assumption for climatic properties but could be less so for soils, given the potential for local variability in soil characteristics. While there is published information available on the soils of these experimental plots, it was decided to base estimating BFIHOST solely on FEH catchment descriptors, in order to replicate typical practice for greenfield runoff estimation using FEH methods.

At North Wyke, there was no suitable downstream gauged catchment from which to scale an estimate of QMED. To test the sensitivity of the results to different approaches to estimating plot-scale catchment descriptors, four sets of catchment descriptors were estimated from the FEH CD-ROM, depicted in Table 4.

Whilst a gauged catchment was available downstream of the Pontbren plot, catchment descriptors upstream and downstream of the site were used to estimate a 0.5 km^2 lateral catchment containing the plot from which to scale flows, reflecting current recommended practice. The derivation of this catchment is shown in Table 5.

Table 4 - Catchment descriptors - North Wyke

Catchment descriptors	Description	AREA (km^2)	DPLBAR (km)	DPSBAR (m/km)
Downstream of site	The smallest catchment containing the site shown on the FEH CD-ROM.  (Plot shown by red circle.)	3.51	2.1	61.3
Upstream of site	The catchment immediately upstream of the site.  (Plot shown by red circle.)	3	1.68	62.2
Headwater	An adjacent headwater catchment – might be more representative of plot scale due to lack of defined watercourse.  (Plot shown by red circle.)	0.5	0.53	50.4

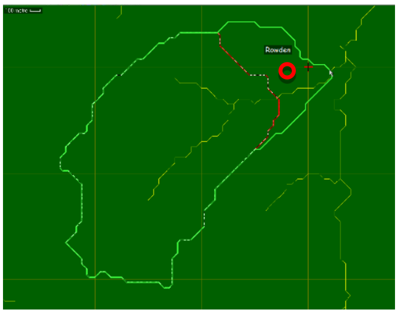
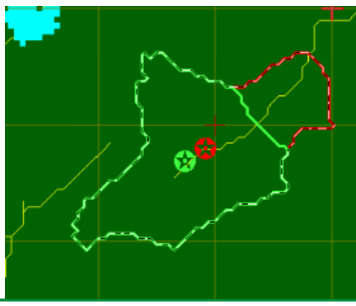
Catchment descriptors	Description	AREA (km^2)	DPLBAR (km)	DPSBAR (m/km)
Lateral catchment	Catchment descriptors representing the intervening area between downstream and upstream of site.  (Plot shown by red circle.)	0.51	0.9	56

Table 5 - Catchment descriptors - Pontbren

Catchment descriptors	Description	AREA (km^2)	DPLBAR (km)	DPSBAR (m/km)
Lateral catchment	Catchment descriptors representing the intervening area between downstream and upstream of site. 	0.48	0.59	79.8

Note: For the lateral catchments, representing intervening areas rather than true catchments, AREA was calculated as the difference between upstream and downstream catchment areas. DPLBAR was calculated using information on the upstream and downstream DPLBAR values along with the longest drainage path descriptor (LDP) and area weighting. DPSBAR was calculated from area weighting. It should be noted that calculation by area weighting does not always give accurate results in the case of small intervening areas.

Four alternative estimates of catchment descriptors were used for the North Wyke plots, compared to only one for Pontbren, because the former have no gauged catchment downstream. Therefore, multiple ways of estimating catchment descriptors for a plot, where no downstream gauged data are available, were investigated.

Of these catchment descriptor sets, the lateral catchment was considered the most representative of the plot scale, given the adjustments based on area. Therefore, these catchment descriptors were used as the basis for an additional uncalibrated scenario to better represent the plot scale, comprised of using plot area and a DPLBAR value adjusted for plot area. The lateral catchment descriptors, with plot area, were used in both calibrated scenarios for North Wyke.

The scenarios used are detailed in Tables 6 and 7.

Table 6 - ReFH method scenarios - Pontbren

Scenario	Details
Calibrated 1	Catchment descriptors from gauged catchment, adjusted AREA for plot
Uncalibrated 1	Catchment descriptors from gauged catchment – result scaled by AREA
Uncalibrated 2	Catchment descriptors from gauged catchment – adjusted AREA and DPLBAR for plot
Uncalibrated 3	ReFH applied using lateral catchment descriptors – adjusted AREA and DPLBAR for plot
Uncalibrated 4	Lateral catchment descriptors – result scaled by AREA

Table 7 - ReFH method scenarios - North Wyke

Scenario	Details
Calibrated 1 – Plot 4	Lateral catchment descriptors - adjusted AREA for plot
Calibrated 2 – Plot 8	Lateral catchment descriptors - adjusted AREA for plot
Uncalibrated 1	ReFH applied using lateral catchment descriptors – result scaled by AREA
Uncalibrated 2	Headwater catchment descriptors – result scaled by AREA
Uncalibrated 3	Catchment descriptors downstream of site – result scaled by AREA
Uncalibrated 4	Catchment descriptors upstream of site – result scaled by AREA
Uncalibrated 5	Lateral catchment, adjusted AREA and DPLBAR for plot

The model parameters used for the ReFH scenarios are displayed in Appendix A. Throughout, the comparison between calibrated and uncalibrated versions of the ReFH model was made to assess the magnitude of difference between the methods. This was mainly to establish whether calibration of the model is necessary, when using the ReFH method for estimating plot scale runoff. This is important, given that for the vast majority of cases, plot scale runoff data will not be available, as well as the full ReFH software package being a requirement for calibrating ReFH models.

5.2 ReFH1 results

The results for Pontbren and North Wyke are presented in Tables 8 and 9.

The design rainfall used has been generated using the storm duration recommended by the ReFH method based on the model parameters used. This approach was complemented by a sensitivity analysis (Section 5.3).

Table 8 - Pontbren results - ReFH method

Scenario	QMED (l/s)
Calibrated 1	6.10
Uncalibrated 1	3.98
Uncalibrated 2	12.20
Uncalibrated 3	11.80
Uncalibrated 4	5.43

Table 9 - North Wyke results - ReFH method

Scenario	QMED (l/s)
Calibrated 1 - Plot 4	11.43
Calibrated 2 - Plot 8	10.76
Uncalibrated 1	9.53
Uncalibrated 2	11.79
Uncalibrated 3	6.90
Uncalibrated 4	7.69
Uncalibrated 5	20.55

QMED values estimated using the ReFH method vary significantly depending on the method used and the catchment descriptor approach adopted.

Tables 8 and 9 demonstrate that estimates of QMED scaled from downstream catchments are lower than those derived from ReFH models calibrated to observed plot-scale events or from adjusting catchment descriptors to the plot scale. Most significantly, the uncalibrated five scenarios at North Wyke and the uncalibrated 2 and uncalibrated 3 scenarios at Pontbren demonstrate the impact of adjusting AREA and DPLBAR to represent the plot scale, rather than simply scaling the result by area, the resulting reduction in time to peak leading to much higher estimates of QMED. For all three plots, the uncalibrated application of ReFH at the plot scale leads to considerably higher peak flows than when ReFH parameters are estimated from runoff data. A possible implication is that the regression equations for estimating model parameters result in overestimating peak flows when they are applied at the plot scale, perhaps due to underestimating time to peak. This would not be surprising given that the plot-scale values for DPLBAR are very much smaller than those for any of the gauged catchments used to develop the regression models.

At North Wyke, uncalibrated scenarios 1 to 4 all involve applying ReFH to various small catchments and scaling the result down by area. Using headwater catchment descriptors (uncalibrated 2) produces a higher estimate of QMED than the lateral catchment descriptors (uncalibrated 1). This may be due to the shorter DPLBAR for the headwater catchment.

5.3 Sensitivity analysis

It would be expected that the critical storm duration for a plot scale catchment may be shorter than for a larger containing catchment. A sensitivity analysis of storm duration was carried out to determine whether the storm duration equation used in ReFH correctly identified the critical duration for values of T_p estimated either from catchment descriptors or calibration. The results of the sensitivity analysis are displayed in Figures 10 and 11. The results from Tables 8 and 9 are represented as the red point series on each graph.

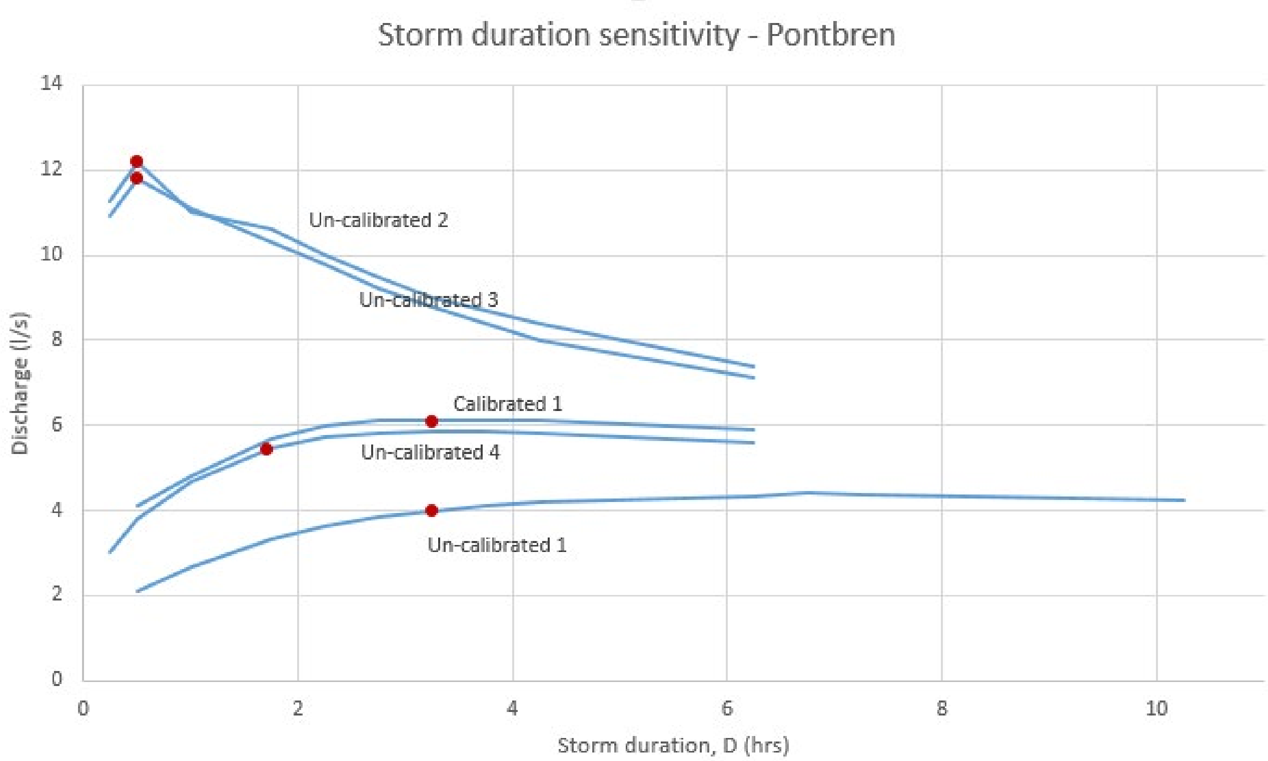


Figure 10 - Sensitivity analysis – storm duration, Pontbren

Figure 10 plots the results of the sensitivity analysis of storm duration at Pontbren for:

- un-calibrated 1
- un-calibrated 2
- un-calibrated 3
- un-calibrated 4
- calibrated 4

The x-axis shows the storm duration (from 0 to 10 hours). The y-axis shows the discharge (from 0 to 14 l/s). The red dot on each line shows the results from Tables 8 and 9.

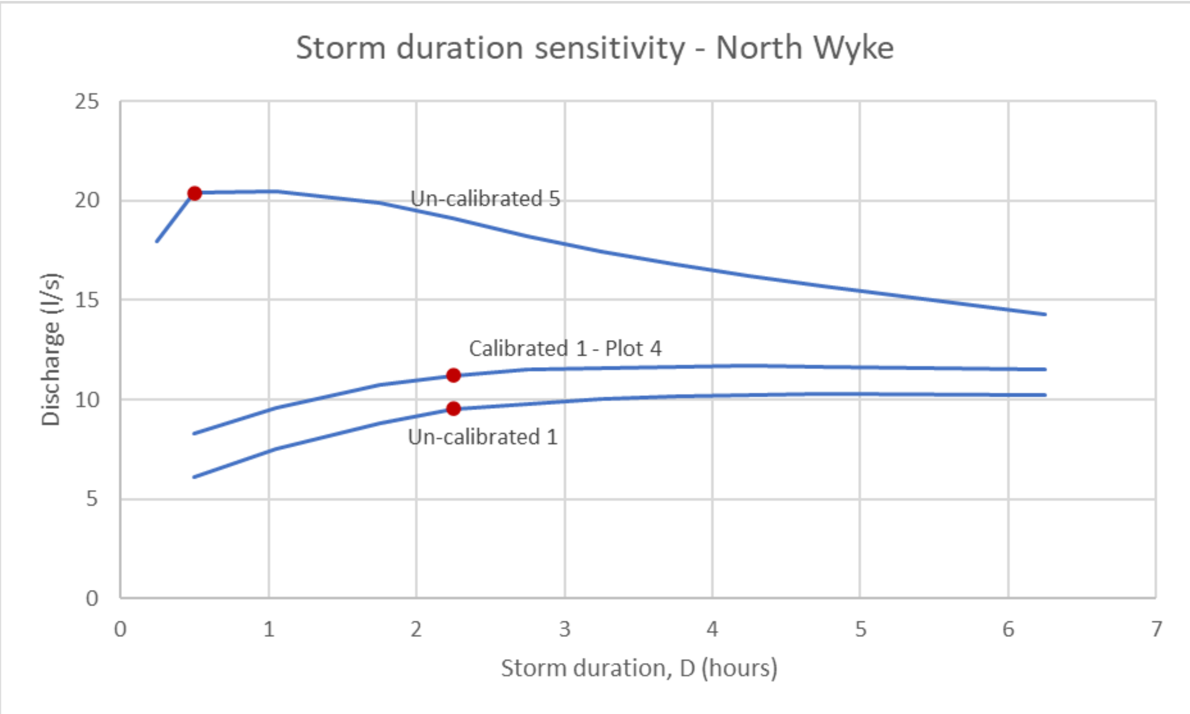


Figure 11 - Sensitivity analysis – storm duration, North Wyke

Figure 11 plots the results of the sensitivity analysis of storm duration at North Wyke for:

- un-calibrated 1
- un-calibrated 5
- calibrated 1 – plot 4

The x-axis shows the storm duration (from 0 to 7 hours). The y-axis shows the discharge (from 0 to 25 l/s). The red dot on each line shows the results from Tables 8 and 9.

Significant inferences can be made from the results of the sensitivity analysis.

Firstly, the critical storm duration is only fully captured by ReFH when AREA and DPLBAR are adjusted for the plot scale. This relates to estimating the T_p value in the ReFH model and its effect on storm duration.

Secondly, the effect of adjusting catchment descriptors to the plot scale is demonstrated in scenarios uncalibrated 2 and uncalibrated 3 for Pontbren and uncalibrated 5 for North

Wyke, where QMED estimates are higher (as demonstrated in Tables 8 and 9), and critical storm durations are shorter as would be expected for a plot scale catchment. The crucial observation, however, is that this relationship is not reflected in the calibrated scenarios – short critical storm durations are not produced. This is because optimising model parameters to observed events results in longer T_p values, the result being lower estimates of QMED.

It should be noted, though, that some of the curves of peak flow against storm duration are very flat, so that there is little difference in peak flow for a wide range of storm durations.

6. FEH statistical method

QMED has been estimated using a regression equation based on catchment descriptors, and from analysis of the observed plot data, providing a comparison between the plot and catchment scale.

6.1 QMED equation

The equation used to calculate QMED from catchment descriptors is given in Kjeldsen and others (2008). In a similar way to the ReFH method, different scenarios for catchment descriptors were tested. For the statistical method, results were tested for the effect of accounting for catchment area before calculating QMED (applying the equation to the plot area), or after (scaling the final result by the plot – containing catchment area ratio). Given the lack of further information regarding catchment descriptors at the plot scale, the estimation of QMED using the QMED equation are assumed the same descriptors for both plot 4 and plot 8 at North Wyke. The results for all plots are presented in Table 11.

Table 11 - Statistical method - QMED equation

Site	Scenario	Catchment	QMED (l/s)
Pontbren	Catchment descriptors from gauged catchment – result scaled by AREA	n/a	5.40
Pontbren	Catchment descriptors from gauged catchment – adjusted AREA for plot	n/a	14.50
Pontbren	Catchment descriptors from lateral catchment – result scaled by AREA	n/a	7.00
Pontbren	Catchment descriptors from lateral catchment – adjusted AREA for plot	n/a	14.10
North Wyke	Catchment descriptors from ungauged catchment – result scaled by AREA	Adjacent headwater catchment	11.08
North Wyke	Catchment descriptors from ungauged catchment – result scaled by AREA	Downstream catchment	8.28
North Wyke	Catchment descriptors from ungauged catchment – result scaled by AREA	Upstream catchment	8.59
North Wyke	Catchment descriptors from ungauged catchment – result scaled by AREA	Lateral catchment	10.10
North Wyke	Catchment descriptors from ungauged catchment – adjusted AREA for plot	Adjacent headwater catchment	19.78
North Wyke	Catchment descriptors from ungauged catchment – adjusted AREA for plot	Downstream catchment	19.74
North Wyke	Catchment descriptors from ungauged catchment – adjusted AREA for plot	Upstream catchment	20.03
North Wyke	Catchment descriptors from ungauged catchment – adjusted AREA for plot	Lateral catchment	18.08

6.2 Peaks-over-threshold analysis

QMED can also be estimated using observed flow peak data over a particular threshold (POT), as the weighted sum of two consecutive ranked events using an equation based on the period of record contributing to the data set. The method is outlined in full detail in FEH Volume 3 (Robson and Reed, 1999). The results of the POT analysis are shown in Table 12.

Table 12 - POT analysis

Site	Period of record (years)	Event ranks required	Weighting factor (for second-ranked event)	QMED (l/s)
Pontbren	~3	2, 3	0.100	4.24
North Wyke Plot 4	2	2, 3	0.895	25.39
North Wyke Plot 8	2	2, 3	0.895	69.89

When analysing the results from Table 12 the incomplete flow data records for both sites, as discussed in Section 3.1, must be considered.

At Pontbren, the period of record analysis (Section 3.1) suggested that significant flood peaks may have occurred during a period of missing data. This includes the largest peak during the available record at gauge 6. While there is no guarantee it would be the largest peak at the plot scale, it is highly probable that the QMED value calculated for Pontbren using POT would be higher had this peak been included, considering the ranks of the events used in calculating QMED.

The results for North Wyke demonstrate a much higher QMED estimate for plot 8 than plot 4. This is unexpected, given that the area of both plots is so similar and their proximity would make any significant variation in plot characteristics, such as soil type, improbable. The difference is due to their differing response to the event in January 2007, which exhibits a large peak in plot 8 and a much lower peak in plot 4 (blue arrows in Figures 12 and 13). This leads to differing rank two events between the two plots, as highlighted with red arrows in Figures 12 and 13, and therefore the large event of 2 June 2008 is not used in the QMED estimate for plot 4.

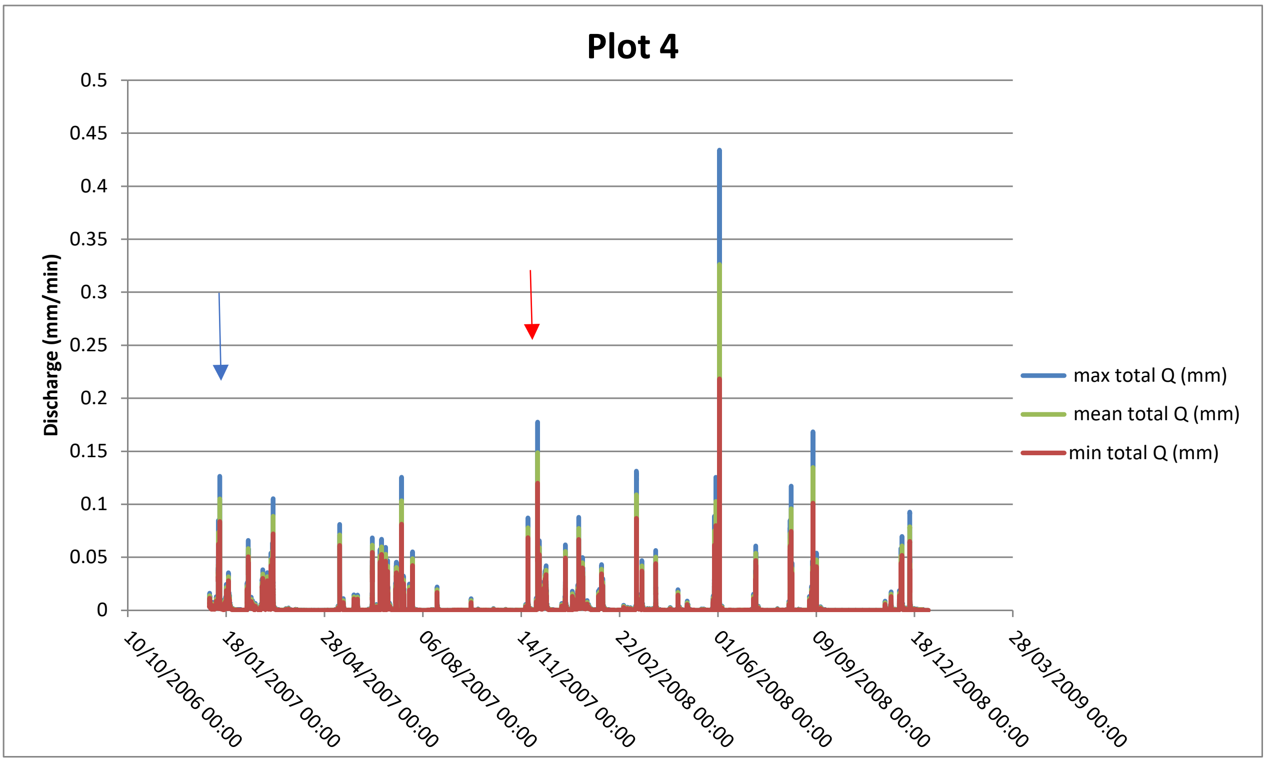


Figure 12 - North Wyke flow peak analysis (plot 4)

The graph in Figure 12 shows the flood peaks at North Wyke (plot 4) between 10 October 2006 and 28 March 2009 (x-axis). The y-axis shows the discharge from 0 to 0.5 mm/min. The bars show:

- max total Q (mm): blue
- mean total Q (mm): green
- min total Q (mm): red

The blue arrow shows the lower flood peak in plot 4 than in plot 8 (January 2007). The red arrow shows the differing rank two events between the two plots.

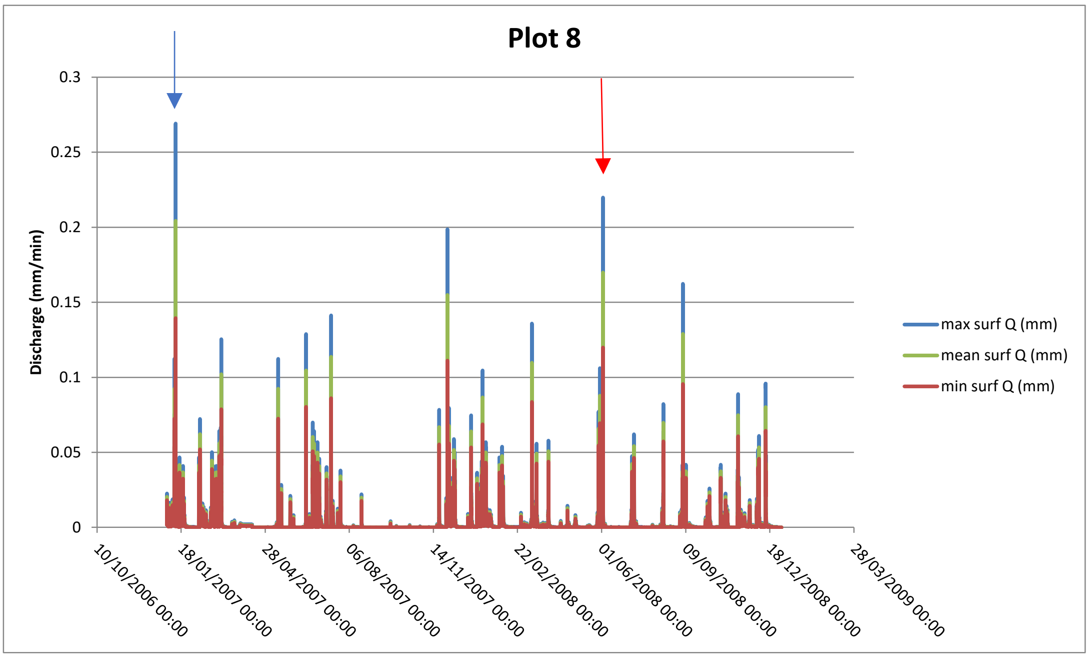


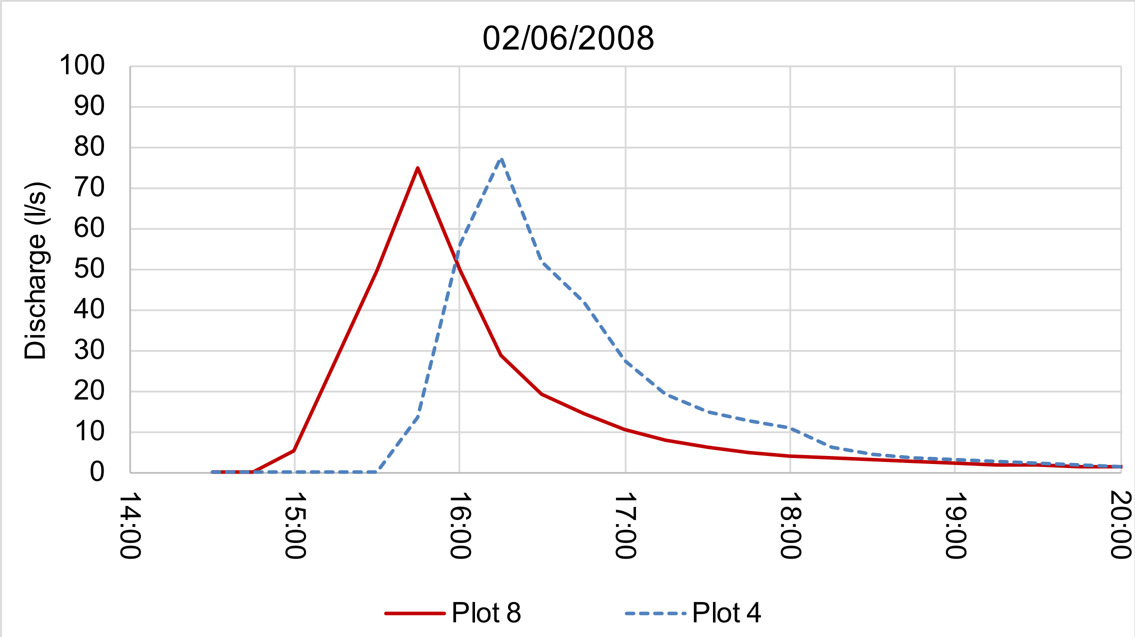
Figure 13 - North Wyke flow peak analysis (plot 8)

The graph in Figure 13 shows the flood peaks at North Wyke (plot 8) between 10 October 2006 and 28 March 2009 (x-axis). The y-axis shows the discharge from 0 to 0.3 mm/min. The bars show:

- max surf Q (mm): blue
- mean surf Q (mm): green
- min surf Q (mm): red

The blue arrow shows the higher flood peak in plot 8 than in plot 4 (January 2007). The red arrow shows the differing rank two events between the two plots.

The differing magnitude of the peaks between plots 4 and 8 for the January 2007 event is unusual, as demonstrated by observation that in other large events the two plots produce responses of near-identical magnitude (Figure 14).



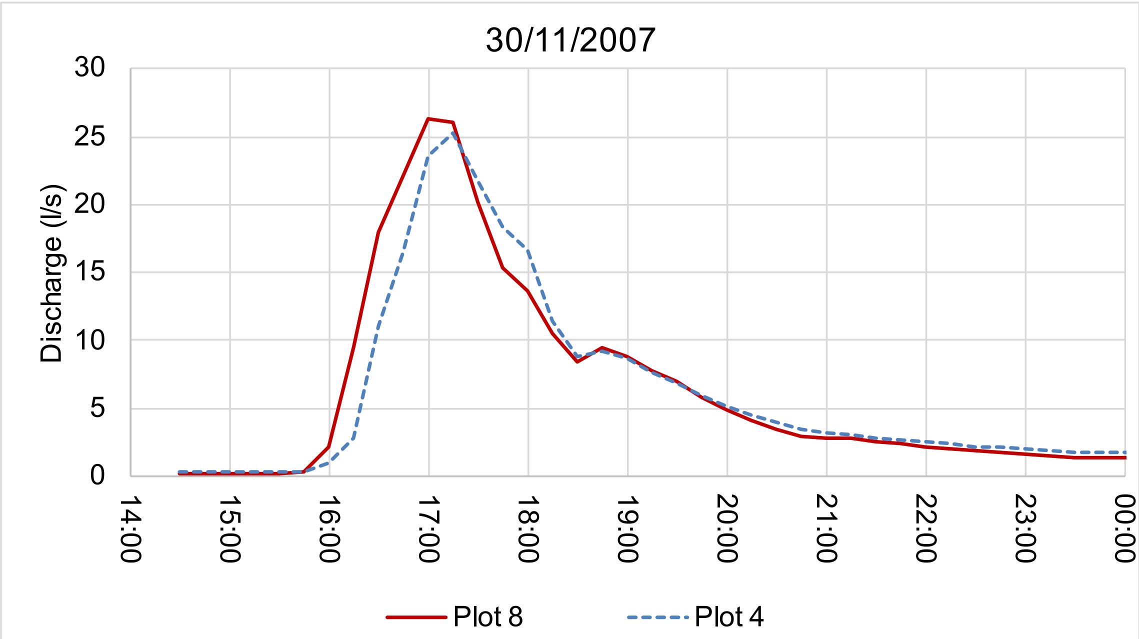


Figure 14 - Plot scale event hydrograph comparison - North Wyke

The two line graphs in Figure 14 plot the discharge at plot 8 (red line) and plot 4 (blue dashed line) for two time periods:

- top graph: from 14:00 to 20:00 on 2 June 2008 (x-axis) and based on a discharge measurement of 0 to 100 l/s (y-axis)
- bottom graph: from 14:00 on 30 November 2007 to 00:00 on 1 December 2007 (x-axis) and based on a discharge measurement of 0 to 30 l/s (y-axis)

7. Results and summary discussion of the ReFH1, calibrated ReFH1 and FEH statistical results

In order to provide an assessment and comparison of the methods used to estimate QMED, results have been collated for each site and are presented in Figures 15 and 16. Results for the ReFH method have been modified from Tables 8 and 9, where storm duration sensitivity testing revealed a higher QMED estimate using the critical storm duration. To simplify the graph for North Wyke, the only results shown for scaling down QMED by area are those based on the catchment descriptors of the lateral catchment.

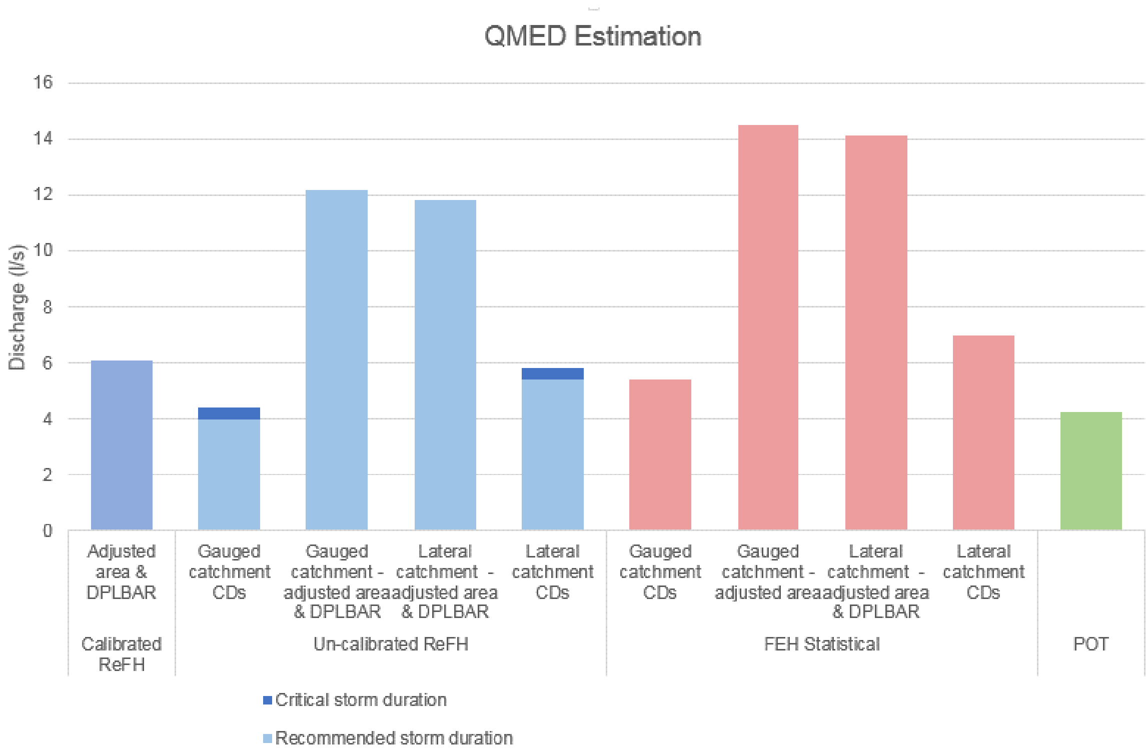


Figure 15 - Collated QMED estimation results, Pontbren

The bar chart in Figure 15 shows a comparison of the methods used to estimate QMED at Pontbren. The y-axis shows the discharge from 0 to 16 l/s (x-axis). The vertical bars on the y-axis show results for:

- calibrated ReFH (adjusted area and DPLBAR) – purple bar.
- un-calibrated ReFH – blue bars:
    - gauged catchment CDs
    - gauged catchment - adjusted area & DPLBAR
    - lateral catchment - adjusted area & DPLBAR
    - lateral catchment CDs
- FEH statistical – red bars:
    - gauged catchment CDs

- gauged catchment - adjusted area
- lateral catchment - adjusted area & DPLBAR.Lateral catchment CDs

- POT – green bar

On the four bars the un-calibrated ReFH results, dark blue sections signify the critical storm duration, and the light blue sections signify the recommended storm duration.

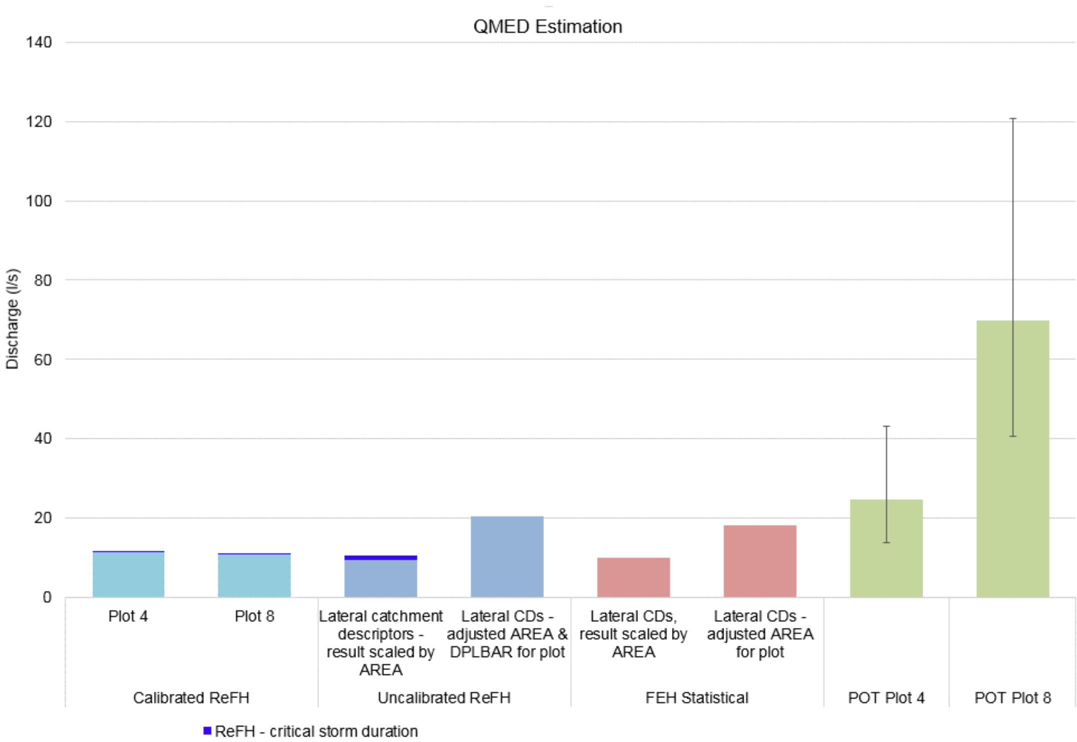


Figure 16 - Collated QMED estimation results, North Wyke

The bar chart in Figure 16 shows a comparison of the methods used to estimate QMED at North Wyke. The y-axis shows the discharge from 0 to 140 l/s (x-axis). The vertical bars on the y-axis show results for:

- calibrated ReFH – light blue bars:
  - plot 4
  - plot 8
- un-calibrated ReFH – dark blue bars:
  - lateral catchment descriptors – result scaled by AREA
  - lateral CDs – adjusted AREA & DPLBAR for plot
- FEH statistical – red bars:
  - lateral CDs – result scaled by AREA
  - lateral CDs – adjusted AREA for plot
- POT – green bars:
  - plot 4
  - plot 8

Certain relationships can be observed in the above figures, demonstrating some level of consistency in results between sites. Methods based on the plot scale (where catchment descriptors have been adjusted to the plot scale or QMED has been estimated directly from POT data at the plot scale) generally produce higher estimates of QMED than methods scaling results from larger catchments (the exception is the calibrated ReFH method, see Section 5.2). This is consistent with the results in Figures 7, 8 and 9, showing scaled downstream flows tend to underestimate plot-scale flows.

The POT estimate of QMED does not replicate this relationship at Pontbren. This is probably because the estimate has been affected by missing data (Figure 4), especially during the winter of 2008 which would likely contain several large events. It is possible that a more complete data series would results in a considerably larger estimate of QMED at Pontbren. At North Wyke, POT data from the two plots apparently yield very different estimates of QMED. As already discussed, this is difficult to believe given the similarity and proximity of the plots. The confidence intervals for estimates of QMED on plots 4 and 8 marginally overlap (Figure 16). Despite this apparent discrepancy, for both plots it can still be concluded that the ReFH and FEH statistical methods, whether applied at the plot scale or the catchment scale and then scaled down, appear to underestimate QMED at North Wyke.

Ideally, all the estimates of QMED using POT data would be improved with complete, and longer, data records. This would allow more robust testing of the hypothesis that scaled FEH methods underestimate peak plot-scale flow.

The findings of this study are consistent with those reported by Rodda and Hawkins (2012) who analysed runoff data from plot 8 at North Wyke for the period September 2006 to December 2008. The estimated 100-year flow from the IH Report 124 method was exceeded on six occasions during this short period, with the highest recorded flow being at least over three times the estimated 100-year flood.

In discussing the applicability of the IH 124 method for calculating plot-scale runoff, Rodda and Hawkins (2012) state that:

“The assumption that a method derived from observed stream flow data for catchments ranging between 0.5 and 20 km^2 can be used at a 1 ha-sized plot by taking an area proportional relationship is unrealistic and does not demonstrate an understanding of catchment hydrology. The time lag and attenuation associated with the stream flow even in a small catchment will have a considerable impact so that the peak flow measured in a stream, and averaged on a per hectare basis, would be considerably less than that coming off a one hectare plot.”

IH124 is criticised by Rodda and Hawkins (2012) for not taking any account of slope and land use, both factors which have been observed to influence runoff rates from neighbouring plots at North Wyke. Even the type of grazing livestock is thought to have an effect, with much higher surface runoff observed (visually) from plots grazed by sheep compared with those grazed by cattle, which leave a thicker sward. Similar criticisms could be made of the FEH statistical or ReFH methods when applied at the plot scale.

8. Modelling plot-scale runoff using the ReFH2-FEH99 design package

8.1 Overview

This section presents an assessment of the ReFH2 FEH99 design package for estimating peak flow and runoff for the North Wyke and Pontbren data sets sourced by JBA for this project.

Both of these plots are in relatively high rainfall areas and both are dominated by clay soils. Both sites have a moderately high gradient of 12% (Pontbren) and 5 to 10% (North Wyke).

The previous sections compared the performance of the original ReFH methods against the measured data and considered the simulation results obtained using both calibrated model parameters (calibrated against observed events with the plot-scale records) and various approaches to estimating ReFH v1 (ReFH1) design package parameters.

This section considers version 2 of the ReFH methods and software implementation (ReFH2; Wallingford HydroSolutions 2016). This report also considers the sensitivity of plot-scale simulation results obtained using ReFH to the choice of model parameters.

Applying ReFH2 to estimating QMED within the two experimental plots is presented in Section 8.2, and Section 9 draws together conclusions and recommendations from this analysis.

During the recent development of ReFH2, the relationships between the calibrated model parameters (T_p, $C_{max,}$ BL, and BR) and catchment descriptors, which enable the model to be applied within a catchment without calibration, were revised and separate design packages developed for the FEH 99 rainfall and FEH13 rainfall models. At the time of the work presented in this report only the FEH99 design package was available to use. Using the FEH99 model also allows a direct comparison with the ReFH1 results presented in the earlier sections of this report.

The small catchments phase 1 report identified that the FEH methods in small catchments are better at producing estimates than older methods such as ADAS 345 and Institute of Hydrology (IH)124. Within England and Wales (before Natural Resources Wales was formed) the Environment Agency recommended that the FEH methods should be used for small fluvial catchment and plot-scale greenfield runoff estimates. Including the catchment drainage network geometry descriptors DPLBAR (mean drainage path length) and DPSBAR (mean drainage path slope) in estimating T_p and BL within ReFH limits the usefulness of the model for plot-scale purposes. Not unexpectedly DPLBAR, the mean drainage path length, has a strong relationship with catchment area (AREA). SAAR (standard average annual rainfall) may be used as a proxy for DPSBAR since catchments with high topographic gradients along the drainage paths are mainly located within higher rainfall regions. These are both gridded descriptors and can be extracted for plot-scale applications. Alternative models (using AREA as an alternative descriptor to DPLBAR and SAAR as an alternative to DPSBAR) were therefore also developed to apply the ReFH model directly in estimating greenfield runoff rates and volumes at the plot scale.

The structure of each of the equations for estimating C_{max}, T_p, BL, and BR and measures of predictive performance are presented in Table 13. Two equations for T_p and BL are presented: those using catchment geometry-based descriptors and those based on non-geometric descriptors. As the ReFH2 software incorporates an explicit model for estimating urban runoff, while the $URBEXT_{2000}$ descriptor is used in developing the T_p and BL parameters, the $URBEXT_{2000}$ value is set to zero when used to derive these parameters within ungauged catchments.

Table 13 - Structure and performance of each equation for estimating the four controlling parameters, T_p, C_{max}, BL and BR using catchment descriptors

Controlling parameter	Equation	R^2	fse
T_p	$T_p = aPROPWET^bDPLBAR^c(1 + URBEXT_{2000})^dDPSBAR^e$	0.80	1.30
T_p	$T_p = aPROPWET^bAREA^c(1 + URBEXT_{2000})^dSAAR^e$	0.71	1.36
C_{max}	$C_{max} = aPROPWET^b\exp(cBFIHOST)$	0.60	1.29
BL	$BL = aPROPWET^bDPLBAR^c(1 + URBEXT_{2000})^dBFIHOST^e$	0.35	1.49
BL	$BL = aPROPWET^bAREA^c(1 + URBEXT_{2000})^dBFIHOST^e$	0.31	1.48
BR	$BR = aPROPWET^bBFIHOST^c$	0.36	1.51

The values of R^2 and factorial standard error in Table 8.1 indicate that there is only minimal loss of performance in the alternative equations for T_p and BL that do not include DPLBAR and DPSBAR. As they do not include catchment descriptors relating to the geometry of the river network, the alternative equations are possible to use at the plot scale.

8.2 Plot-scale evaluation of ReFH2

For both North Wyke and Pontbren the QMED (2-year) peak flow was estimated using the ReFH2 methodologies. The motivation for plot-scale runoff estimation has been discussed in both the phase 1 report and the earlier sections of this report. The analysis of the plot-scale data (see Section 4) highlights that the hydrographs for the Pontbren plot runoff are considerably 'peakier' than for the corresponding downstream catchment. This peaky response was also observed in the North Wyke plot-scale runoff.

The analysis within Sections 5 and 6 considered a range of approaches to estimating suitable design model parameter sets for ReFH1 and compared the estimates of QMED obtained with these sets with the estimate of QMED obtained using locally calibrated ReFH parameters. The analysis used the ReFH1 parameter equations for this analysis and identified that, as the area used as the basis for estimating catchment descriptors approaches the plot-scale area, the resultant estimates of QMED peak flow significantly exceed the estimates obtained using the locally calibrated parameter sets. Considering the reported design and calibrated parameter values and noting the lack of sensitivity of peak flow estimates to the modelling of baseflow, this result is mainly a consequence of the catchment descriptor equation for estimating T_p yielding small values of significantly less than one hour. The lowest value of T_p for Pontbren was 0.16 hours and for North Wyke, 0.26 hours. In contrast, the locally calibrated value of T_p was 0.73 hours for Pontbren, and 1.23 hours (Plot 4) and 1.43 hours (Plot 8) for North Wyke.

This highlights an important point when applying the ReFH design package to very small catchments. The original calibration of ReFH within the catchments used to develop the design package was carried out using a data time step of one hour. Therefore, the information in sub-hourly rainfall data and streamflow response was averaged out within these calibration data sets. While it is entirely reasonable to calibrate ReFH at shorter time steps than one hour (as was the case with the local calibration of the model within the earlier plot-scale application within the report), the lowest value of T_p that the design package equations should be used to estimate is one hour. This argument also applies to BL but as discussed, the baseflow is a small proportion of the overall peak flow and is always greater than one hour for the obvious hydrological reasons.

Within this report, the sensitivity of the results obtained at the plot scale to the choice of model parameters has been further explored using ReFH2. ReFH2 has been used for this analysis as the software supersedes ReFH1 (now withdrawn from distribution), and the evaluation across the HiFlows-UK data set shows the software is an improvement on ReFH in terms of prediction accuracy and precision.

Three parameterisation sets have been applied for each site. For each parameter set, the sensitivity of the results has been evaluated using values of T_p in the range [0.1,1.5] hours and in increments of 0.1 hour. The three parameter sets used were the:

- locally calibrated values of C_{max}, BL and BR ('ReFH calibrated')
- full catchment ReFH2 design package ('ReFH2')
- plot-scale ReFH2 design package using SAAR and AREA rather than DPSBAR and DPLBAR ('ReFH2 plot-scale')

The catchment descriptors for the lateral catchments containing the plots were used together with the areas of the plots. As T_p has been treated as a sensitivity parameter, the only difference between the two ReFH2 sets is the estimate of BL. The results are presented within the following sub-sections for the two plots.

North Wyke

The recommended duration was selected based on the point value of SAAR and a T_p of one hour, resulting in a duration of 2.1 hours and a time step of 0.1 hour. This ensures that the same rainfall event was used for each scenario.

Table 14 presents the main parameter values. The initial conditions were set using the design package defaults. The peak flows generated for each value of T_p are presented in Table 15. Figure 17 presents the hydrograph simulated using the ReFH calibrated parameters and a T_p of 1, while Figure 18 presents the hydrograph using the ReFH2 catchment descriptor parameters and a T_p of 1.

The values of QMED estimated using the full set of locally calibrated parameters were 11.2 and 10.76 l/s respectively at the plot 4 and plot 8 sites.

Considering the simulation results for a value of T_p = one hour, the ReFH2 parameter sets provide estimates that are broadly consistent with the estimates obtained using the calibrated model parameters. When compared to the calibrated value of T_p, the ReFH2 estimates are both about 10% lower than the values obtained with the calibrated model parameters.

When considering the hydrographs, the very high value of C_{max} identified by local calibration produces a hydrograph with a very high baseflow (because of the indirect dependency of BF_0 on C_{max}). The high value of C_{max} also inevitably results in a reduced direct runoff component.

Table 14 - North Wyke ReFH parameters

Parameter	ReFH calibrated	ReFH2	ReFH2 plot-scale
C_{max}	1148	241.4	241.4
BL	14.49	24.9	19.5
BR	0.52	0.8	0.8

Table 15 - Peak flows for the 2-year return period using variable T_p values for each parameter set

T_p	ReFH calibrated (cumecs)	ReFH2 (cumecs)	ReFH2 plot-scale (cumecs)
0.5	0.021	0.018	0.018
0.6	0.019	0.017	0.017
0.7	0.018	0.015	0.016
0.8	0.017	0.014	0.014
0.9	0.016	0.013	0.013
1	0.015	0.012	0.013
1.1	0.014	0.012	0.012
1.2	0.013	0.011	0.011
1.3	0.013	0.010	0.011
1.4	0.012	0.010	0.010
1.5	0.012	0.009	0.009

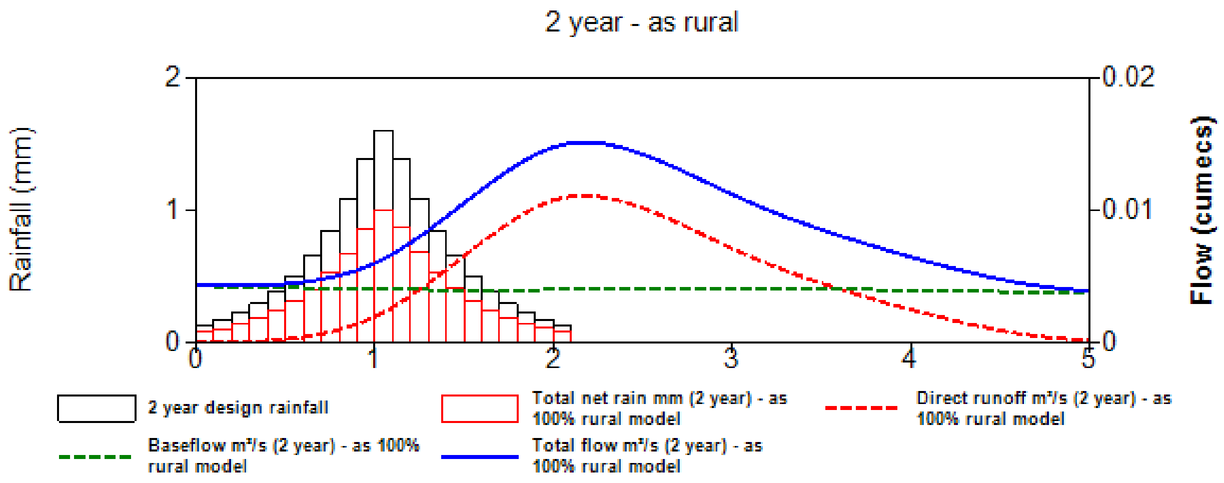


Figure 17 - Hydrograph for the 2-year event using the calibrated parameters and a T_p of one hour

Figure 17 is the hydrograph simulated using the ReFH calibrated parameters and a T_p of 1. It shows rainfall (from 0 to 2 mm) and flow (cumecs) from 0 to 0.01 in relation to:

- 2 year design rainfall (black boxes)
- total net rain in mm (2 year) – as 100% rural model (red boxes)
- direct runoff (m^2/s – 2 year) - as 100% rural model (dashed red line)
- baseflow (m^2/s – 2 year) - as 100% rural model (dashed green line)
- total flow (m^2/s – 2 year) - as 100% rural model (solid blue line)

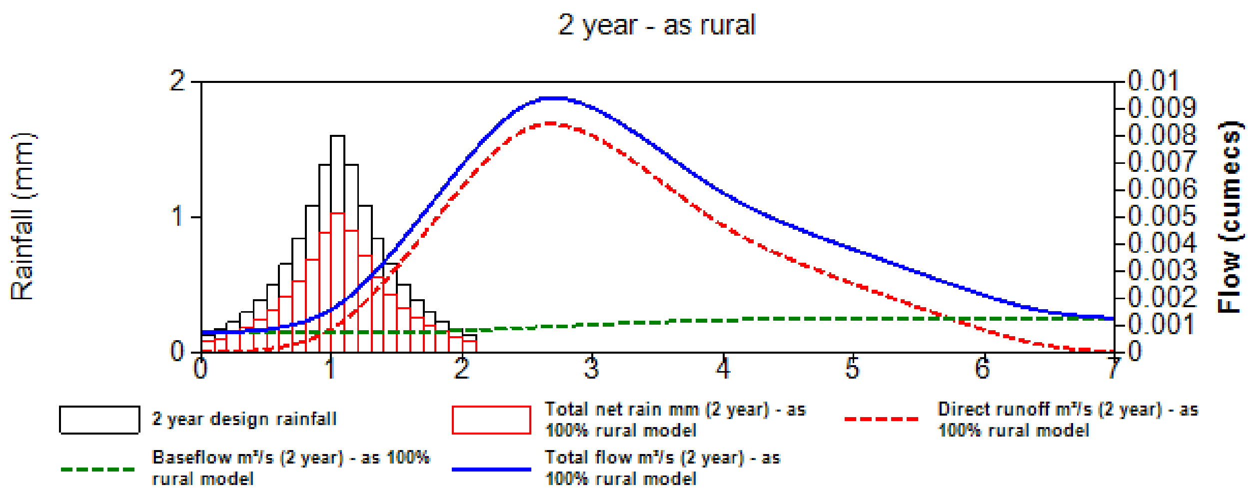


Figure 18 - Hydrograph for the 2-year event using the ReFH2 catchment descriptor parameters and a T_p of one hour

Figure 18 is the hydrograph simulated using the ReFH2 catchment descriptor parameters and a T_p of 1. It shows rainfall (from 0 to 2 mm) and flow (cumecs) from 0 to 0.01 in relation to:

- 2 year design rainfall (black boxes)
- total net rain in mm (2 year) – as 100% rural model (red boxes)

- direct runoff (m^2/s – 2 year) - as 100% rural model (dashed red line)
- baseflow (m^2/s – 2 year) - as 100% rural model (dashed green line)
- total flow (m^2/s – 2 year) - as 100% rural model (solid blue line)

Pontbren

The same modelling approach was applied at Pontbren. The event duration was set at 2.3 hours and was used with a data interval of 0.1 hours.

Table 16 presents the parameters used for each scenario and Table 17 presents the peak flows generated for each value of T_p. Figure 19 presents the hydrograph for the 2-year return period using the ReFH2 catchment descriptor parameters and a T_p of one hour. The value of QMED obtained using the calibrated model parameters, as reported within the earlier sections, was 6.1 l/s.

Considering the results at a value of T_p = 1, the plot-scale results obtained using ReFH2 are essentially identical to the estimates generated using the fully calibrated model parameters. In this case, the calibrated model parameter set yields a lower baseflow than that obtained using the design package estimates.

Table 16 - Pontbren ReFH parameters

Parameter	ReFH calibrated	ReFH2	ReFH2 plot-scale
C_{max}	249.35	213.60	213.60
BL	6.91	23.10	16.40
BR	0.49	0.73	0.73

Table 17 - Peak flows for the 2-year return period using variable T_p values for each parameter set

T_p	ReFH calibrated (cumecs)	ReFH2 (cumecs)	ReFH2 plot-scale (cumecs)
0.5	0.009	0.009	0.009
0.6	0.008	0.008	0.008
0.7	0.008	0.007	0.008
0.8	0.007	0.007	0.007
0.9	0.006	0.006	0.006
1.0	0.006	0.006	0.006
1.1	0.006	0.006	0.006
1.2	0.005	0.005	0.005
1.3	0.005	0.005	0.005
1.4	0.005	0.005	0.005
1.5	0.005	0.004	0.005

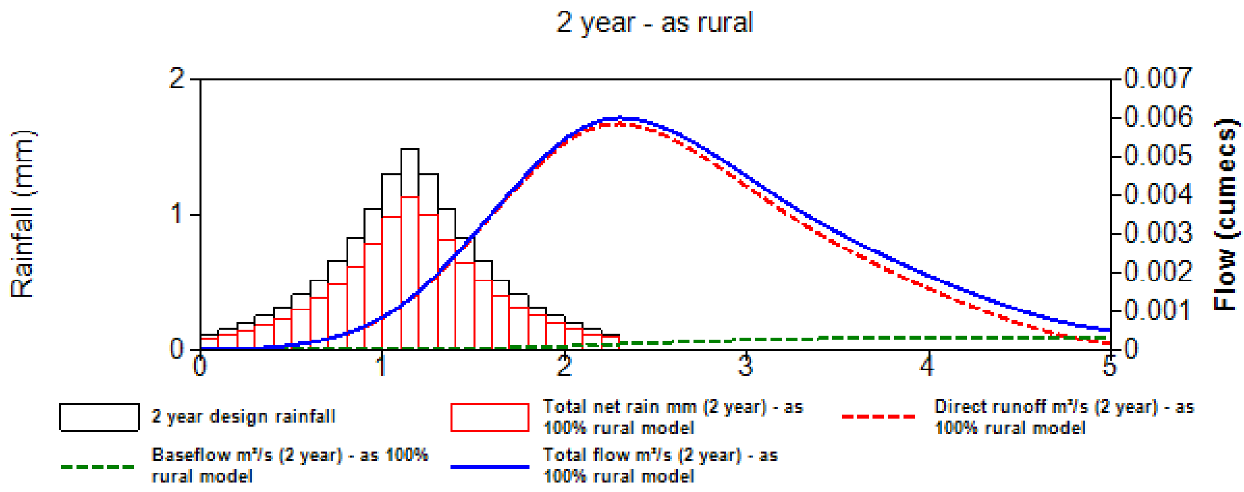


Figure 19 - Hydrograph for the 2-year event using the ReFH2 catchment descriptor parameters and a T_p of one hour

Figure 19 is the hydrograph for the 2-year return period using the ReFH2 catchment descriptor parameters and a T_p of one hour. It shows rainfall (from 0 to 2 mm) and flow (cumecs) from 0 to 0.007 in relation to:

- 2 year design rainfall (black boxes)
- total net rain in mm (2 year) – as 100% rural model (red boxes)
- direct runoff (m^2/s – 2 year) - as 100% rural model (dashed red line)
- baseflow (m^2/s – 2 year) - as 100% rural model (dashed green line)
- total flow (m^2/s – 2 year) - as 100% rural model (solid blue line)

9. Implications for estimating plot-scale runoff

An extended discussion of the issues associated with translating flows from catchment scale to plot scale is included in Appendix B of the report on phase 1 of this project. One point that can easily be overlooked is that the purpose of estimating plot-scale runoff in a flood risk assessment is often to develop a scheme for managing runoff from a development site that will avoid any increase in flood risk further downstream. In this case, the river flow hydrograph at the downstream site (and the plot's contribution to it) is more important than the runoff hydrograph at the outlet of the plot. If that is the case, there may be less cause for concern over the finding that scaled FEH methods tend to underestimate peak plot-scale flow for drainage design applications. The corresponding greenfield runoff rates used to limit discharge rates will also be potentially underestimated and therefore give a conservative discharge rate in terms of mitigating downstream flood risk.

However, plot-scale runoff estimates are also required for assessing surface water flood risk local to the development site, for example, in which case an accurate estimate at the plot scale itself is desirable. Rodda and Hawkins (2012) point out that underestimating plot-scale runoff rates would result in underestimating local surface water flood risk in cases where greenfield areas are retained as part of developed sites for the design of sustainable urban drainage systems (SuDS).

It has been highlighted that 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 T_p that can be resolved from this time step has a value of one hour. Therefore, although the catchment descriptor equations can produce estimates of T_p that are less than one hour, these are not valid and a minimum value of one hour should be set.

The ReFH2 design package was applied to the plots to estimate QMED. In this application, the design parameters were estimated using the catchment descriptors reported by JBA for the lateral (or incremental) catchments containing the plots, the areas of the plots were used to define the model extent and T_p was set to one. In this application, the QMED estimates generated were very close to those estimated using ReFH model parameters calibrated against the experimental flow and rainfall data for the plots.

The outcomes of the calibration work would suggest that the ReFH model framework is broadly appropriate for simulating runoff generation from these relatively impermeable plots. The outcomes obtained by applying the ReFH2 design package with T_p constrained to a lower limit of one hour suggest that the design package is also appropriate for applying at the plot scale. The results obtained using the full design package and the plot-scale design package yield similar results, however using the plot-scale equations enables the method to be applied directly where there is no definable drainage network.

The phase 1 report also points out that a significant assumption is made in transposing design flows to the plot scale: that the plot has similar hydrological properties to the catchment from which flows are transposed. Without some consideration of site-specific characteristics, there would be a risk that a greenfield runoff rate applied as an average across a small catchment may be too high or too low for a particular development site whose soils or land use are not typical of the catchment average. Underestimating a greenfield runoff rate would result in over-design of storage volumes intended to mitigate runoff from impermeable surfaces (Rodda and Hawkins, 2012). Overestimation would result in the limiting discharge from a development being set higher than the actual greenfield rate, and therefore an increase in downstream flood flows.

With these considerations in mind, the phase 1 report suggested that the decision to translate flood estimates from catchment scale to plot scale should be accompanied by an assessment of whether the study site is representative of the surrounding catchment area. Knowing the characteristics of a site, it should be possible to assess whether runoff rates at the plot scale are likely to be greater or less than the average rate for the surrounding small catchment. The approach has the disadvantage of relying on judgement and therefore an element of subjectivity, but it allows for a site-specific understanding of uncertainty in the flow assessment, and is in keeping with the analytical approaches now accepted for river flow estimation.

10. Limitations

The main limitations affecting the results obtained in this study are discussed above. However, there are additional limitations which, if rectified, would improve confidence in the results.

10.1 Data availability

Number of sites

In total, data from three plots across two sites were available for analysis. This small set inevitably raises questions over the robustness of the conclusions made above, given that, ideally, these phenomena would need to be observed on many more plot scale catchments. Data from other sites would help test the hypothesis developed from the limited analysis carried out to date; that scaled FEH methods underestimate plot-scale peak flow.

Unfortunately, the prospects for extending the data set are not promising. An extensive search has not found any other suitable plot-scale runoff data available at reasonable cost. Rodda and Hawkins (2012) were not able to find any plot-scale runoff data (other than that at North Wyke) from UK sites with similar temporal resolution. However, they quoted results from experiments in Belgium and northern France with measured peak flows of up to 200 l/s/ha.

ReFH

The ability to calibrate ReFH model parameters was limited by the temporal resolution of the data: rainfall data for North Wyke was provided at an hourly interval, as was runoff data for Pontbren. A finer resolution would be preferable for calibration on small catchments and plots. However, the outcomes of the application of the ReFH2 design package would suggest that the added value might not be as great as one might expect.

The calibration of ReFH models for both North Wyke and Pontbren assumed a sine curve for potential evaporation (PE). Daily MORECS data would be a preferred source of evaporation data for ReFH model calibration.

11. Conclusions and recommendations

This study was carried out to evaluate the suitability of FEH methods when applied at plot-scale, paying particular attention to the different ways in which these methods might be adapted. The following conclusions and recommendations are made.

Higher estimates of QMED are obtained when the ReFH model parameter values are calculated from scaled catchment descriptors for lateral catchments (Section 5.1) than when scaling the modelled peak flow from a larger downstream catchment by area. This part of the study used ReFH1, as it was carried out before ReFH2 was released. However, the results are expected to apply to ReFH2.

Similarly, the FEH statistical method can be used either by scaling the results for a downstream catchment by area or by using the plot's area together with downstream SAAR, FARL and BFIHOST (potentially setting FARL to one if there are no waterbodies in the plot). Higher estimates of QMED are obtained when using the plot's area than scaling QMED from a downstream catchment. This is due to the relationship between QMED and AREA specified in the equation ($QMED = AREA^{0.8510}$…).

ReFH2 introduces plot-scale parameter equations for T_p and BL, which do not use DPLBAR or DPSBAR, neither of which exist independently of a river network. Similar results for QMED are obtained from ReFH2 using either the standard or plot-scale equations. These equations should be used for plot-scale applications of ReFH2.

The ReFH2 design package, with T_p constrained to ≥ 1 hour, is appropriate for plot-scale applications. Therefore, ReFH2, with a minimum T_p value of one hour should be used for plot-scale estimation. This is discussed in more detail within report 6.

Winter storms should be used for all greenfield calculations in ReFH2.

As briefly discussed in Section 7, older methods such as IH124 and ADAS345 are functionally inappropriate and have already been discounted from the analysis.

In all cases, the acceptable level of accuracy varies with the purpose of the analysis: at-site assessments of flood risk require higher levels of accuracy than assessments of contribution to downstream flood risk. Similarly, the purpose of the analysis informs the consequences of underestimation (which may be more likely when scaling flows from downstream catchments by area) and whether or not low estimates are conservative.

It should be noted that the above conclusions and recommendations represent the best that can be made on the very limited data set used in this study, consisting of three plots at two sites. Unfortunately, the prospects for extending this data set, in order to perform additional verification, are not promising.

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