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Probable maximum flood: the potential for estimation in the UK using ReFH2

Tracey Haxton [a,*], Gianni Vesuviano[b], Samuel Pucknell[a] and Thomas Rodding Kjeldsen[c]

[a] Wallingford HydroSolutions, Wallingford OX10 8BA, UK
[b] UK Centre for Ecology & Hydrology, Wallingford OX10 8BB, UK
[c] Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, UK
*Corresponding author. E-mail: tracey.haxton@hydrosolutions.co.uk

TH, 0000-0001-7416-4612

ABSTRACT

The current reservoir safety guidance within the UK recommends the use of the FSR/FEH rainfall-runoff model to estimate PMF (probable maximum flood) peak flows for reservoirs within the highest risk category (A). However, the FSR/FEH model has been superseded by the ReFH2 rainfall-runoff model for all other flood risk purposes in the UK. This study develops a new modelling framework for PMF estimation using ReFH2 by translating the assumptions made within the current FSR/FEH PMF procedure and applying these within the ReFH2 rainfall-runoff model. Peak flows from the methodology are compared with those from the FSR/FEH model for 400+ catchments. The study highlights the potential for ReFH2 to be used as the rainfall-runoff model for all return periods, up to and including the PMF, thereby paving the way for using the ReFH2 model for reservoir safety studies.

Key words: flood estimation, FSR/FEH, probable maximum flood, ReFH, reservoirs and dams

HIGHLIGHTS

- Application of the FSR/FEH rainfall-runoff method for probable maximum flood (PMF) estimation in the UK at 400+ catchments.
- Use of the ReFH2 rainfall-runoff model, often recommended for standard design periods, using the same assumptions as current PMF methods, for PMF estimation.
- Development of a flexible method for PMF estimation that can be improved as further research is completed.

LIST OF SYMBOLS

Symbol	Meaning	Units
BFIHOST19	BFI (baseflow index) estimated using HOST (Hydrology of Soil Types) classification	
BL	Baseflow recession constant (or lag)	hours
BR	Baseflow recharge	
C_{ini}	Initial soil moisture depth	mm
C_{max}	Maximum soil moisture depth	mm
CWI	Catchment wetness index	mm
DPLBAR	Mean drainage path length	km
DPR_{CWI}	Dynamic percentage runoff dependent on *CWI*	%
DPR_{RAIN}	Dynamic percentage runoff dependent on *P*	%
DPSBAR	Mean drainage path slope	km
EM-2h	Estimated maximum 2-h rainfall	mm
EM-24h	Estimated maximum 24-h rainfall	mm
P	Total design storm depth	mm
PMF	Peak flow of a PMF event	m^3/s
PMP	Total depth of a design PMP storm	mm
PR	Percentage runoff	%
PROPWET	Index of proportion of time that soils are wet	
SAAR	Standard Annual Average Rainfall	mm

SPR	Standard percentage runoff	%
SPRHOST	SPR estimated using HOST (Hydrology of Soil Types) classification	
Tp	Unit hydrograph time to peak	hours
URBEXT	FEH index of fraction urban extent	

INTRODUCTION

Reservoir safety in the UK is regulated through the Reservoirs Act 1975 (RA75). The safety regulations require the estimation of the probable maximum flood (PMF) for reservoirs which fall within category A, where failure of a reservoir can result in loss of life. The ICE (2015) states that the PMF represents 'the flood hydrograph resulting from PMP [probable maximum precipitation] and, where applicable, snowmelt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions'. Current guidelines for estimating the PMF are summarised by Pether & Fraser (2019) and detailed within the fourth edition of the Floods and Reservoir Safety publication (ICE 2015). These guidelines stipulate that the PMF is estimated using the method outlined in Flood Estimation Handbook (FEH) volume 4 (Houghton-Carr 1999); a restatement of the original method described in the Flood Studies Report (FSR) (NERC 1975). While the original FSR method has been replaced by the revitalised flood hydrograph (ReFH) method for design flood estimation (Kjeldsen *et al.* 2005; WHS 2019), the estimation of PMF still relies on the original FSR method.

Depending on the category of dam, flood hydrographs (and peak flows) are required for the 150-, 1,000- and 10,000-year events as well as the PMF. For each dam category, a different combination of design rainfall and rainfall-runoff models may be recommended. A subset of these is presented in Table 1.

While the ReFH2 model is not cited within Pether & Fraser (2019) for use in 10,000-year return period events, simulation of design events up to a return period of 10,000 years was tested and enabled within the ReFH2.3 software released in November 2019 (WHS 2022). Thus, the PMF event is the only return period where the FSR/FEH rainfall-runoff model is still required to be used. Many of the issues relating to the current estimation of PMF within the UK are summarised in Faulkner & Benn (2019) and included in a recent review of current methods by the Environment Agency (EA 2023). Many of the areas highlighted for improvement require substantial investment and further research. The aim of this study is not to resolve the larger issues but to investigate whether it is feasible to use a consistent rainfall-runoff model (ReFH2) for all return periods, up to and including the PMF event. Notably, Pucknell *et al.* (2020) present a framework for estimating PMF using the ReFH2 model, by translating the FSR/FEH procedure into an equivalent ReFH2 procedure. Here, we develop these methods further to show that PMF peak flows (and hydrographs) can be estimated using the PMP rainfall event, the ReFH2 rainfall-runoff model and the assumptions associated with the current PMF method. Updates can be incorporated within the framework without recourse to older methods.

The FSR/FEH and ReFH2 models are conceptual unit hydrograph rainfall-runoff models and are described in subsequent sections. Both can be utilised in ungauged catchments as parameters can be estimated from catchment descriptors. This is a requirement of the method as many reservoired catchments (or those where reservoirs may be planned) are ungauged.

Current method for PMF estimation

PMP estimation

The estimation of the PMP event is independent of that for design rainfall events of lower return periods. Details are provided by Houghton-Carr (1999) and only a summary provided here. The baseline data for the method uses the FSR estimated

Table 1 | Rainfall depth-duration-frequency model and rainfall-runoff model used for flood hydrology at UK dams (excerpt from Pether & Fraser (2019))

	150-year return period	1,000-year return period	10,000-year return period	PMF
Rainfall depth-duration-frequency model	FEH2013	FEH2013	FEH2013	FSR
Rainfall-runoff model	FSR/FEH and/or ReFH and/or ReFH2	FSR/FEH and/or ReFH2	FSR/FEH ReFH2[a]	FSR/FEH

[a]ReFH2.3, released in 2019, allows users to estimate the 10,000-year hydrograph.

maximum (EM) rainfall depths for the 2-h and 24-h events (*EM-2h* and *EM-24h*) which are interpolated or extrapolated for different duration events. A 'nested' approach is used in which, for each subsequent larger duration, the shorter duration event PMPs are retained. Areal reduction factors and seasonal correction factors are also applied. For the winter event, the 100-year snowmelt event may be added to both the PMP and antecedent conditions. In the past, there has been confusion on how to apply snowmelt and a generic 42 mm/day has often been used. Recent guidance (DEFRA 2022) has clarified that the Hough & Hollis (1997) method, based on observed snowmelt records, should be applied.

PMF estimation

The PMP event is used as input data to the FSR/FEH rainfall-runoff model. This is an update of the FSR rainfall-runoff model, utilising catchment descriptors released in the FEH, Volume 5 (Bayliss 1999). The model consists of three main components: a loss model, a routing model and baseflow component model.

Within the loss model, a static percentage runoff is used through the event (Equation (1)).

$$\begin{aligned} &PR = SPR + DPR_{CWI} + DPR_{RAIN} \\ &DPR_{CWI} = 0.25(CWI - 125) \\ &DPR_{RAIN} = \begin{cases} 0 & P \leq 40\text{mm} \\ 0.45(P-40)^{0.7} & P > 40 \end{cases} \end{aligned} \tag{1}$$

where *PR* is the percentage runoff, *SPR* is the standardised percentage runoff (based on SPRHOST, where HOST is the Hydrology Of Soil Types, Boorman *et al.* 1995), DPR_{CWI} is based on the *CWI* (catchment wetness index) an indication of pre-event saturation and DPR_{RAIN} is event specific, based on the rainfall depth of the event, *P*.

Routing is based on a unit hydrograph, with time-to-peak *Tp*, which can be estimated from catchment characteristics (*DPSBAR*, *PROPWET*, *DPLBAR* and *URBEXT*).

Baseflow is constant and can be estimated using the CWI and catchment descriptors (*AREA* and *SAAR*; the Standard-period i.e. 1961–1990, Average Annual Average Rainfall).

To reflect the 'ultra conservative assumptions' (NERC 1975) required for PMF estimation, adjustments are made to the rainfall and rainfall-runoff model. These adjustments are summarised in Table 2.

As summarised by the Environment Agency (2023), many of these adjustments are somewhat arbitrary and have not been updated since the FSR (NERC 1975).

The adjustment to the antecedent conditions (not winter-specific conditions), is based on the assumption that an event 2 times the duration of the PMP rainfall model falls prior to the event, producing the *EMa*, Equation (2). This is then used to estimate the CWI, Equation (3).

$$EMa = 0.5[(ARF_{5D} \times EM\_5Dh) - (ARF_D \times EM\_Dh)] \tag{2}$$

where *EMa* is the antecedent rainfall, ARF_{5D} and ARF_D are the areal reduction factors for the 5D and 1D durations and

Table 2 | Components of the FSR/FEH rainfall-runoff model for standard design and PMF events

Component	FSR/FEH standard design	FSR/FEH PMF
Rainfall	FSR or FEH99	PMP Winter: additional input from snowmelt and rainmelt.
Loss Model	Static *PR*	Static *PR*, increased due to antecedent conditions. Winter: additional antecedent rainfall from snowmelt and rainmelt. Winter: Frozen ground; *SPRHOST*[a] is set to a minimum 53%.
Routing	Triangular unit hydrograph, controlled by *Tp*[b]	Triangular unit hydrograph, reduce *Tp* by a third.
Baseflow	Static baseflow	Static baseflow linked to increased *CWI*.

[a]*SPRHOST* is the standard percentage runoff derive using the HOST soil classification.
[b]*Tp* is the unit hydrograph time-to-peak.

EM_5Dh and EM_Dh are the seasonal EM depths for the 5D and 1D durations.

$$CWI = 125 + EMa(0.5^{D/24}) \tag{3}$$

where CWI is the catchment wetness index, EMa is the antecedent rainfall and D is the duration in hours of the event.

The revitalised flood hydrograph rainfall-runoff model (ReFH)

The revitalised flood hydrograph rainfall-runoff model (ReFH) was first developed by Kjeldsen *et al.* (2005). The ReFH conceptual model has a number of improvements over the existing FSR/FEH rainfall-runoff model, summarised in Table 3. In addition, the development used more calibration data and higher-resolution soils data.

The ReFH loss model has one static parameter, C_{max}, which represents the maximum soil moisture depth and an initial soil moisture depth (C_{ini}), which can vary between (observed) events.

For a given event, the percentage runoff PR is calculated as a function of C_{max}, C_{ini} and rainfall depth P (mm), as presented in Equation (4).

$$PR = \frac{C_{ini}}{C_{max}} + \frac{P}{2C_{max}} \tag{4}$$

The first term on the right-hand side relates to the antecedent conditions, while the second part represents the dynamic rainfall effects. This form is similar to the FSR/FEH loss model, presented in Equation (1). Unlike the FSR/FEH loss model, the losses in the ReFH model are calculated for each time step of the simulation to account for the wetting-up of the soil during the flood event.

Subsequently, there have been a number of additional updates including the incorporation of the FEH13 rainfall model (Stewart *et al.* 2013), improved parameterisation (as well as a bespoke calibration for Scotland) and, more recently within ReFH2.3, inclusion of water balance features. The latest release also increased the maximum return period, such that the 1 in 10,000-year event can now be estimated.

The ReFH2 model is recommended for use, and widely utilised, within flood risk assessments where return periods up to 1,000 years are required. It is widely accepted that the form of the ReFH rainfall-runoff model offers considerable improvements over the FSR/FEH rainfall-runoff model and the ReFH2 rainfall-runoff model is recommended for use within reservoir studies for lower return period estimates. Use of the ReFH2 model for PMF estimation would therefore offer improvement relating to the structure of the model, as well as allowing consistency across all return periods. While by no means the largest issue relating to PMF estimation, consistency will better enable users to make informed decisions relating to differences between lower and higher return period peak flows without the complicating factor that these have been estimated using different rainfall-runoff models.

Many of the adjustments summarised in Table 2 can be directly applied to the ReFH2 model. The least straightforward adjustment to apply relates to the initial soil moisture. In winter, there is the additional complication that frozen ground also needs to be taken into account. Pucknell *et al.* (2020) presented a method, trialled on 14 catchments that illustrated how the ReFH2 rainfall-runoff model could use the assumptions of the PMF method to estimate the PMF. The PMF C_{ini} $(C_{ini\_PMF})_i$ required to produce the increase in PR from the FSR/FEH rainfall-runoff model within ReFH2, was first estimated

Table 3 | The components of the conceptual unit hydrograph FSR/FEH and ReFH rainfall-runoff models

Component	FSR/FEH standard design rainfall	ReFH standard design rainfall
Rainfall	FSR	FEH99/FEH13
Loss Model	Static PR	PR varies spatially and temporally. Parameters are C_{ini}, the initial soil moisture depth and C_{max}, the maximum soil moisture depth.
Routing	Triangular unit hydrograph, controlled by Tp	'Kinked' unit hydrograph, controlled by Tp.
Baseflow	Static baseflow equal to BF_0, the initial baseflow	Varies throughout event. Parameterised by the BL (baseflow recession constant), BR (baseflow recharge) and BF_0.

by rearranging Equation (4). A relationship was then established between the ratio of C_{ini_PMF} to C_{ini} and C_{max} (Equation (5)).

$$\frac{C_{ini\_PMF}}{C_{ini}} = a \times \exp\left(\frac{b}{1,000} \times C_{max}\right) \tag{5}$$

where C_{ini_PMF} is the C_{ini} for the PMF event and a and b are coefficients for either the winter or summer event.

The resulting PMF peak flows were comparable with those estimated using the FSR/FEH rainfall-runoff method.

Aim

The main aim of this study is to develop a framework by which ReFH2 can be used to implement the current PMF methods based on a translation of the assumptions listed in Table 2 from the FSR to the ReFH modelling method. The framework should be sufficiently flexible to ensure that, as further research is completed and any assumptions or datasets are updated, they can be readily translated into operational practice.

Pucknell *et al.* (2020) illustrated that it was possible to estimate the PMF using the ReFH2 rainfall-runoff model. However, there were a number of limitations to this study, including the small study size (14 catchments), the use of the 'recommended duration' only, and the use of the 42 mm/day snowmelt assumption. This study builds on this work by firstly increasing the sample size. Secondly, the 'recommended duration' is the duration which, in the absence of any storage, is estimated to produce the highest peak flows. However, other durations may be necessary as part of reservoir design; ICE (2015) states that PMF estimation with a number of different durations may be required, in the event that the 'recommended' duration is not the 'critical' duration. This study, therefore, aims to develop a method in which any duration can be used. Finally, this study retains the 42 mm/day snowmelt assumption, allowing results from this study to be compared with those reported by Pucknell *et al.* (2020).

DATA

The catchment data were obtained from the NRFA (National River Flow Archive) Peak Flow dataset version 10 (NRFA 2021). This dataset contains catchment descriptors and annual maxima (AMAX) for each gauging station. 467 catchments, smaller than 1,000 km^2 and flagged as 'suitable for pooling', were selected for this study (Figure 1).

The dataset was maximised to capture a good spatial distribution and cross-section of catchment types (although Northern Ireland was excluded due to a lack of digital EM data). The existence of good quality gauged data at these sites also means that the resulting PMF values can be compared with observed AMAX values.

Different methods have been adopted for incorporating effects of urbanisation on storm runoff within the FSR/FEH and ReFH2 rainfall-runoff models. As the aim is to understand the difference between how the two models estimate the PMF, and given that the incorporation of urban impacts may complicate our understanding of this, the rural estimates of PMF are used.

The *EM-2h* and *EM-24h* were obtained from the UKCEH FSR database at the centroids of each catchment; a justified assumption given the comparative aim of the study.

The 100-year snow depth, which limits the snowmelt that may occur, was obtained from a digitised version of Figure 4.7 in the FEH Volume 4 (Houghton-Carr 1999). The mid value of each snow depth contour boundary at the centroid of each catchment was used. Given the resolution of the map and aims of the study, this assumption is justified.

As far as the authors are aware, this dataset represents the largest catchment set for which the FSR/FEH rainfall-runoff PMF has been estimated in the UK.

METHOD

Three main methods, with a fourth for comparison purposes only, were trialled, and the results compared to ascertain the credibility of the proposed ReFH2-PMF modelling framework:

1. Replication of the Pucknell *et al.* (2020) method for a large number of stations. Referred to as the 'Delta *PR* Rec Duration' method.
2. Extension of the Pucknell *et al.* (2020) method to include greater flexibility in duration selection. Referred to as the 'Delta *PR*' method.
3. Development of flexible method with no link to the FSR method. Referred to as the '*Direct Antecedent*' method.

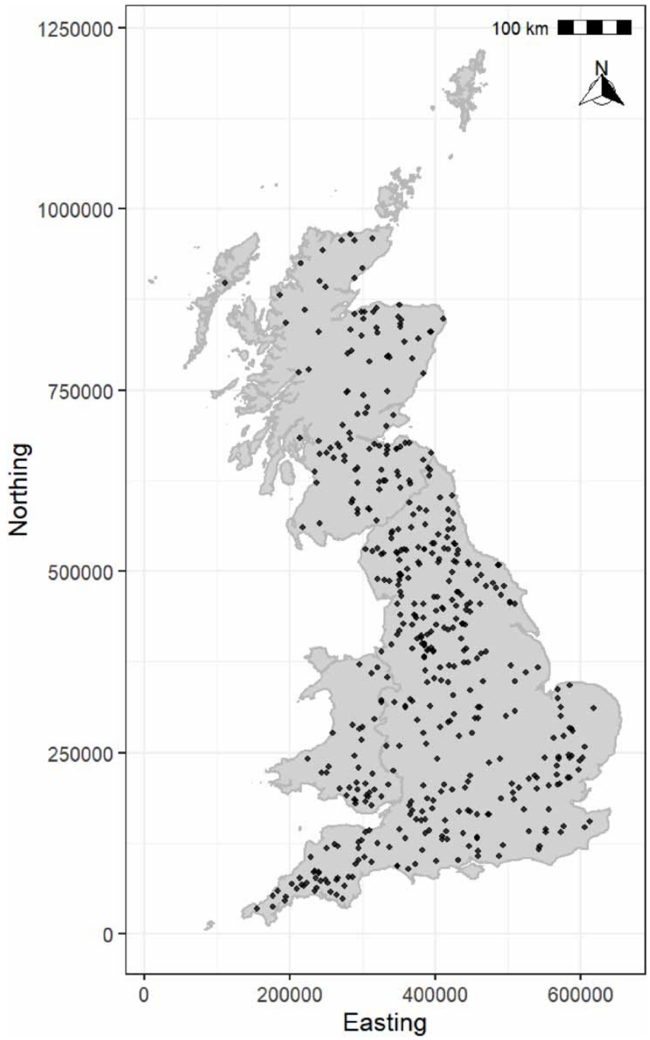

Figure 1 | Location of the 467 catchments (gauging stations) used in the study.

4. The C_{ini_PMF} for ReFH2 was increased using the direct *PR* increase from the FSR/FEH rainfall-runoff model. Referred to as '*FSR/FEH Percent Diff*', this is for comparison purposes only. Methods 1 and 2 are effectively 'fitting' to this dataset.

The results are presented for the recommended duration at each catchment. The recommended duration is based on the *Tp* and *SAAR*, hence these are different for the FSR/FEH and ReFH2 rainfall-runoff models. Where the change in *PR* from the FSR was required ('Delta *PR* Rec Duration', 'Delta *PR*' and 'FSR/FEH Percent Diff' methods), this was calculated using the FSR recommended duration. Application within ReFH2 used the ReFH2 recommended duration.

1. Delta *PR* Rec Duration

The absolute percentage difference in the *PR* for the FSR/FEH rainfall-runoff model between the standard design *PR* and PMF *PR* was calculated for all stations. The revised C_{ini} required to produce this percentage difference was then calculated, and the relationship between the C_{ini_PMF}/C_{ini} and C_{max} was determined. This was used to derive new coefficients for Equation (5), following Pucknell *et al.* (2020). The two models start to deviate in more permeable catchments (as C_{max} increases), with the larger dataset model producing higher C_{ini_PMF}/C_{ini} ratios in these types of catchments. Application of the two models might therefore result in significant differences to the C_{ini_PMF}/C_{ini} ratio, thus peak flows, in highly permeable catchments.

The differences highlight the importance of testing methods within large representative datasets. While reservoirs in the past have been predominantly within small upland catchments, this may change in the future if more lower-altitude flood storage schemes are developed.

2. Delta *PR*

The FSR/FEH rainfall-runoff model was run for a number of durations and the absolute difference in *PR* was then calculated for each. A relationship between the *PR* and input parameters/descriptors was established such that the absolute difference in *PR* could be estimated. The C_{ini} was then adjusted to account for the increasing *PR* using a rearrangement of Equation (4). Since it is the amount of antecedent rainfall that is important, the useful descriptors/data were found to be the ratio of *EM-24h/EM-2h* (an indication of the rate at which the PMP rainfall depths increase with duration), the duration, PMP rainfall depth and *SAAR* (an indication of how wet the catchment is) (Equation (6)).

$$DeltaPR = 11.4 - 5.087 \times \ln(duration) + 3.65(RatEM) + 0.01647PMPRain - 0.001396SAAR \tag{6}$$

where *DeltaPR* is the change in the percentage runoff, *duration* is the length of the event in hours, *RatEM* is the ratio of *EM-24h/EM-2h*, *PMPRain* is the PMP rainfall depth and *SAAR* is the 1961–1990 mean annual rainfall.

3. Direct Antecedent

Within the FSR/FEH application, the *EMa* represents the depth of rainfall that falls prior to the PMP event, over a period two times the duration of the PMP event. Application of Equation (3) then uses this to estimate the PMF *CWI*. This process is replicated within ReFH2 by modelling the *EMa* as a constant-intensity event of 2 times the PMP event duration, with the initial C_{ini} for this 'event' calculated from catchment descriptors. Within ReFH2.3, the 'drainage' feature then reduces the total impact that this has on the soil moisture. The soil moisture depth at the end of the *EMa* event is then used as C_{ini} for the PMP rainfall event.

RESULTS AND DISCUSSION

For each of the three methods, the ReFH2 rainfall-runoff model was applied in combination with the summer PMP event using the ReFH2 recommended duration, the PMP, the reduced *Tp* and the relevant C_{ini_PMF}. For the 'Delta *PR* Rec Duration' and 'Direct Antecedent' methods, the winter PMP event was also run which included the additional snowmelt and rainmelt added to the PMP and antecedent conditions, and a minimum 53% (to represent frozen ground) PR for every timestep.

The PMF summer peak flows for each of the four methods, with the fourth presented for comparison reasons only, relative to the FSR/FEH PMF peak flows, are presented in Figure 2. As the PMF peak flow is unknown any comparison, graphical or statistical, is relative only. Thus, any comparison can only reflect differences between the models/methods, not performance.

Figure 2 shows that the PMF peak flows are of a similar order for all models. The Bias (%, based on ln peak flows), which represents the difference between the models not performance, ranges from 7.59 to 12.7, with the 'Direct Antecedent' method having the lowest Bias.

Figure 3 presents the summer peak flows relative to *SAAR* and *BFIHOST19* (BFI, baseflow index, as estimated using HOST (Hydrology of Soil Types) classification, Griffin *et al.* 2019).

Figure 3 illustrates that, in general, higher peak flows occur in higher *SAAR* and lower *BFIHOST19* catchments. This is confirmed within the Bias which ranges from 24.3 to 27.8 where *SAAR* is greater than 1,000 mm and from 16.1 to 19.6 where *BFIHOST19* is less than 0.65.

There is a greater range of Bias in dry and permeable catchments between the methods with the 'Direct Antecedent' method consistently producing, in general, the lowest peak flows. Where *SAAR* is less than 1,000 mm, the Bias ranges from −9.75 to 0.04 and where *BFIHOST19* is greater than 0.65, the Bias is −40.5 for the 'Direct Antecedent' method and ranges from −20.6 to −29.6 for the other methods. It is useful to note that over 90% of the permeable catchments ($BFIHOST19 > 0.65$) have a *SAAR* less than 1,000 mm.

The difference between the C_{ini_PMF} and the design C_{ini} for the 'Direct Antecedent' and 'FSR/FEH Percent Diff' methods is presented in Figure 4.

Figure 4 illustrates that, while there is a large increase in the C_{ini_PMF} at low C_{ini} values for the 'FSR/FEH Percent Diff' method, this is not found for the 'Direct Antecedent' method. This large difference occurs in catchments where *SAAR* is very low and is

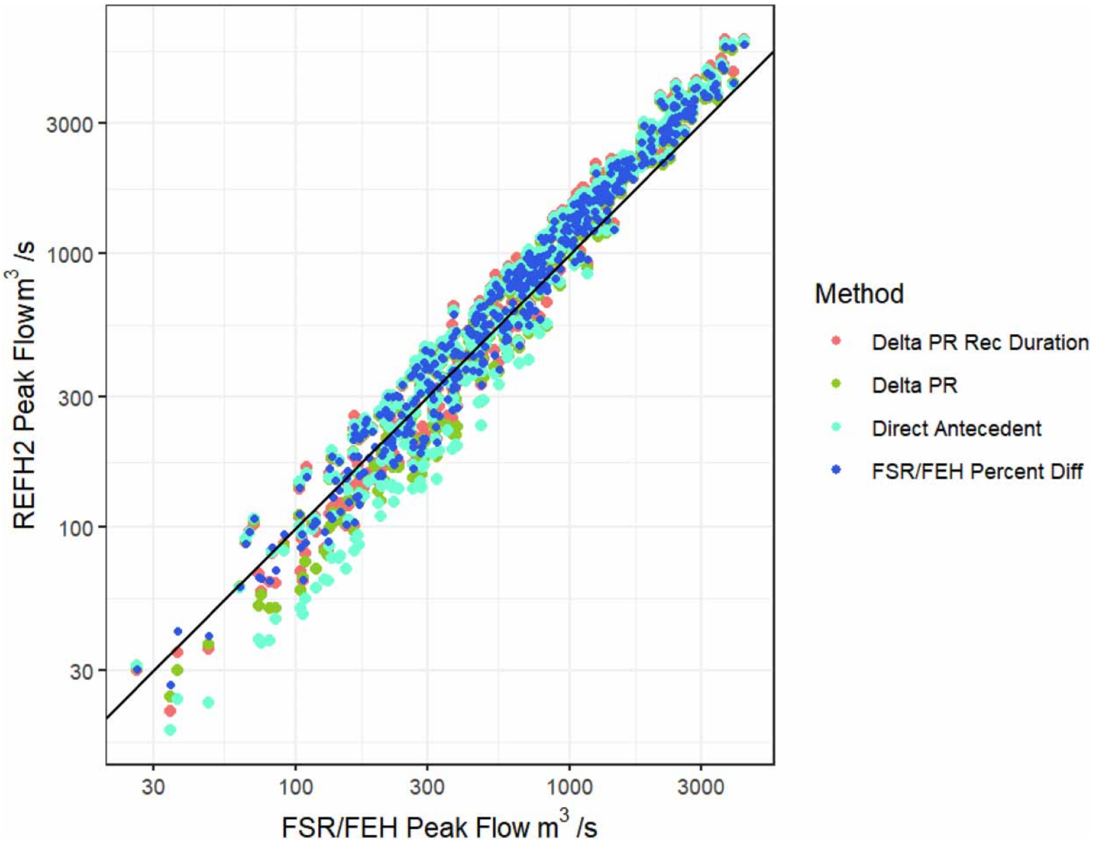

Figure 2 | The summer PMF peak flows estimated using ReFH2 for the four different methods.

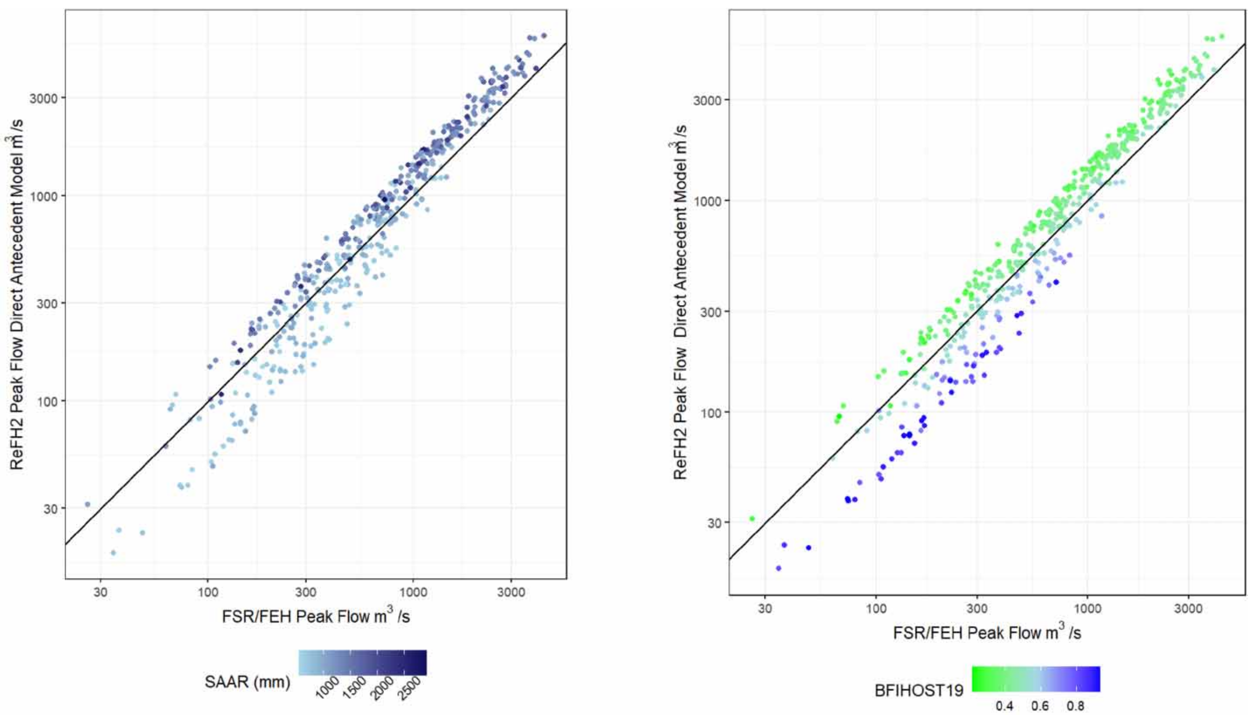

Figure 3 | The summer PMF peak flow using the FSR/FEH rainfall-runoff model and the ReFH2 rainfall-runoff model using the 'Direct Antecedent' method in the context of *SAAR* and *BFIHOST19*.

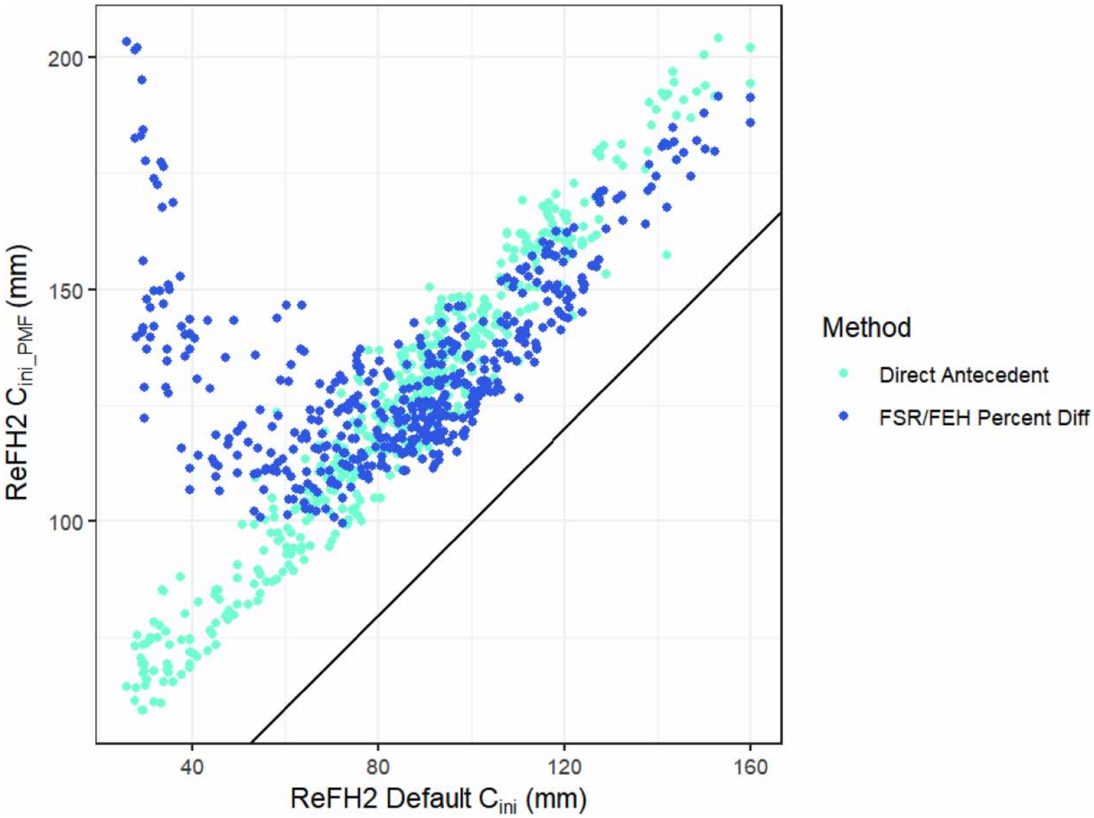

Figure 4 | The ReFH2 design C_{ini} and C_{ini_PMF} for the 'Direct Antecedent' and the 'FSR/FEH Percent Diff' methods.

attributed to the 'disconnect' between the FSR/FEH rainfall-runoff model standard and PMF *CWI* (which then impacts on the *PR*). For lower return periods, *CWI* decreases sharply for catchments with *SAAR* less than 934 mm; above this, the gradient of change is far lower. For the PMF method, the *CWI* is related to the size of the antecedent PMP event. This can result in large increases in *PR* for low-*SAAR* catchments (which in this dataset includes most of the permeable catchments) for the FSR/FEH rainfall-runoff model, which is replicated within the 'Delta PR Rec Duration' and 'Delta *PR*' methods.

This illustrates a weakness of the first two methods, where the implementation within the ReFH2 rainfall-runoff method is based on the impacts as modelled within the FSR/FEH rainfall-runoff model. The 'Direct Antecedent' method does not use these assumptions, hence that method is the most consistent application of the PMF method within the ReFH2 rainfall-runoff model.

For summer events, the differences between the rainfall-runoff models are generally attributed to the differences between the methods for deriving *PR*. The differences between the '*Direct Antecedent*' method and the other methods are driven by the differences in the initial C_{ini} values, particularly within low-*SAAR* catchments. As the permeable catchments are dominated by low-*SAAR* catchments, these differences are marked within this catchment type.

Winter results were produced for the '*Delta PR Rec Duration*' and '*Direct Antecedent*' method. The PMF peak flows for the FSR/FEH rainfall-runoff model and ReFH2 are presented in Figure 5.

Figure 5 shows a greater agreement between the FSR/FEH and ReFH2 rainfall-runoff model peak flow estimates for winter events than summer events. This is borne out by the statistics where the overall Bias values are 6.2 and −5.16 for the 'Delta *PR* Rec Duration' and 'Direct Antecedent' methods, respectively, and the *FSE* (Factorial Standard Error) is 1.19 and 1.2, respectively; note that the *FSE* values for the summer events were higher at 1.28 and 1.36, respectively. The similarity between the two models is attributed to the frozen ground component, whereby the minimum *PR* is set to 53%, producing high percentage runoffs for all catchments.

In general, users apply both the summer and winter events to see which is the critical season for a particular reservoir; it is possible that one may be critical for peak flow and the other for volume.

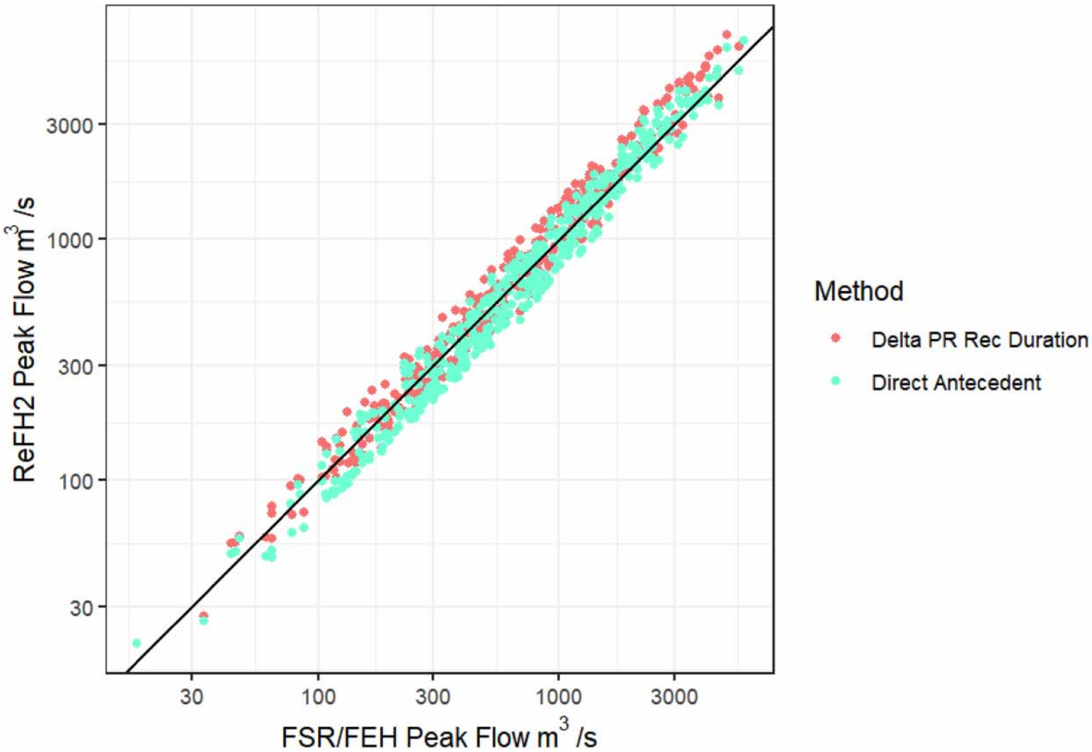

Figure 5 | The winter PMF Peak Flows estimated using ReFH2 for the 'Delta *PR* Rec Duration' and 'Direct Antecedent' methods.

Within the study dataset, for the FSR/FEH rainfall-runoff model, the winter event peak flows are greater than the summer event within 55% of catchments. For the ReFH2 rainfall-runoff model, the summer event peak flow exceeds the winter event within 71% of catchments. For both the FSR/FEH and ReFH2 rainfall-runoff models, the PMP volume is greater for summer, whereas the PRs are lower for summer events. Whether the summer or winter peak flows are higher is therefore attributed to a balance between the peakier, higher rainfall and the lower *PR* for the summer event and the less peaky, lower rainfall, but higher *PR* for winter events. This balance is different between the FSR/FEH rainfall-runoff model and the ReFH2 rainfall-runoff model. This study was completed using a constant snowmelt rate of 42 mm/day, and it is possible that the summer/winter balance would change if the Hough & Hollis (1997) snowmelt methods were used.

A number of studies have sought to determine whether PMFs have been exceeded in the past (Acreman 1989; EA 2023). Potential exceedances have generally been found to occur at ungauged sites, where peak flow has been modelled post-event. However, as this study has produced PMF estimates which represent a large dataset for the UK, it was thought to be advantageous to compare these with the observed AMAX values. Within this dataset, there are no AMAX that are higher than either the FSR/FEH *urban* winter or summer PMF. This does not necessarily mean that no events have exceeded the PMFs at these stations but that no quality-controlled AMAX values within the NRFA Peak Flow dataset have exceeded PMF at present. The winter PMF results may also differ if the H&H snowmelt method is used in the future. A similar assessment for the ReFH2 rainfall-runoff model *rural* PMF estimates (which may be an underestimation of the PMF) shows similar results, although the variability of the PMF for summer events is greater.

The 10,000-year return period peak flow from ReFH2 (rural) was estimated for each of these catchments. For the FSR/FEH rainfall-runoff model, the median ratios of the PMF to the 10,000 year peak flow are 2.5 and 2.1 for winter and summer, respectively. These ratios are related to both *SAAR* (lower ratios for higher rainfall) and *BFIHOST19* (higher ratios for more permeable catchments). The median ratios for the ReFH2 rainfall-runoff model are 2.4 and 2.5 for winter and summer, respectively, with a similar relationship to *SAAR* and *BFIHOST19*.

CONCLUSION

This study has illustrated that the ReFH2 model can be used to estimate the PMF. The 'Delta *PR* Rec Duration' and 'Delta *PR*' methods utilise the outputs of the FSR/FEH rainfall-runoff method for determining how the *PR* changes under PMF conditions. This can result in very large *PR* increases in low-*SAAR* conditions. This is avoided with the 'Direct Antecedent' method, resulting in lower initial conditions (hence lower resulting *PR*) within these catchments. The 'Direct Antecedent' method does not rely on the outputs of the FSR/FEH rainfall-runoff model, which means that any future improvement to the data/assumptions can be directly applied within ReFH2, without recourse to the FSR/FEH rainfall-runoff model.

We have presented a methodology for implementing PMF events within the structure of the ReFH2 rainfall-runoff method which:

1. Is consistent with the current PMF assumptions implemented within the FSR/FEH rainfall-runoff model.
2. Does not require recourse back to the FSR/FEH rainfall-runoff model and the way in which this responds to the PMF event.
3. Is consistent with the rainfall-runoff model used within current design methods in the UK.

In addition, this study has illustrated the importance of testing methods with large datasets representative of the variability of catchment type/climate across the UK.

The dataset produced has been compared with gauged data from the NRFA Peak Flow dataset and has shown that PMFs have not been exceeded at present within this dataset. The median ratios between the FSR/FEH or ReFH2-PMF peak flow estimates and the ReFH2 rural 10,000-year peak flow estimates are between 2.1 and 2.5.

The dataset and methods offer opportunities for further analysis of catchments where current PMF estimates are close to the maximum AMAX or the 10,000 year peak flow estimates. The sensitivities of PMF peak flows to the assumptions within the PMF method (particularly snowmelt) could also be investigated further.

This study has illustrated that the ReFH2 rainfall-runoff model can be used for PMF estimation and the framework is such that, as aspects of the PMF modelling are improved (for example, the PMP or our understanding of how assumptions might be applied) that these can be easily incorporated.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST STATEMENT

Tracey Haxton is an employee of WHS who develop and distribute the ReFH2 software.

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