ReFH2 Science Report

Model Parameters and Initial Conditions for Ungauged Catchments

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For and on behalf of Wallingford HydroSolutions Ltd.

Contents

1 Introduction

The first version of ReFH was first published in 2005 by Kjeldsen et al[1] as a replacement for the original Flood Estimation Handbook (FEH) rainfall-runoff method, the FSR/FEH rainfall-runoff method[2]. The methods are the subject of continuous improvement and the most up-to-date implementation of the methods is though the ReFH2 software.

The most common application of the ReFH2 software is the Design Application. Within the Design Application, an estimate of a rainfall depth over a specified duration and frequency is used within ReFH2 to estimate the flood hydrograph corresponding to that duration and frequency. ReFH2 is used in conjunction with a Depth-Duration-Frequency (DDF) design rainfall model and a corresponding set of design initial conditions. This design application can be applied to river catchments to inform fluvial flood risk or at the scale of a parcel of land to inform pluvial flood risk and drainage design. It is recommended that ReFH2 is used with the FEH13 DDF model[3].

The whole design package comprises:

1. The choice of DDF rainfall model.
2. The estimation of the recommended duration for estimating the event rainfall depth corresponding to a given frequency from the rainfall model.
3. The estimation of the appropriate seasonal (winter/summer) storm hyetograph corresponding to the event rainfall depth.
4. The estimation of ReFH2 initial conditions and model parameters required to estimate the design hydrograph corresponding to the design hyetograph for the required frequency.

The above steps are summarised in the ReFH2 Technical Guide[4] referencing the supporting literature. Whenever possible model parameters should be estimated through careful calibration of the model against observed data, where available. This is achieved using the ReFH calibration tool. In many instances observed data are not available and model parameters are estimated from catchment descriptors.

The ReFH2 model structure is comprised of a rural catchment model component and an urban catchment model component as described in full in the ReFH2 Technical Guide[4]. This Science Report presents the derivation of the catchment descriptor equations for estimating the initial conditions and model parameters for the ReFH2-FEH13 rural catchment design package.

Section 2 first summaries the rural catchment model components. Section 3 then presents the derivation of the model parameter catchment descriptor equations, which were developed for the original ReFH2 design packages and implemented in ReFH2.1 and above (including the water balance version of the FEH13 design package implemented in ReFH2.3 where BFIHOST19 is used instead of BFIHOST).

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[1] T.R. Kjeldsen, E.J. Stewart, J.C. Packman, S.S. Folwell & A.C. Bayliss, 2005. Revitalisation of the FSR/FEH rainfall-runoff method. Defra R&D Technical Report FD1913/TR
[2] Houghton-Carr, H., 1999. Restatement and application of the Flood Studies Report rainfall-runoff method, Flood Estimation Handbook Volume 4.
[3] Stewart EJ, Jones DA, Svensson C, Morris DG, Dempsey P, Dent J E, Collier CG, Anderson CW (2013) Reservoir Safety – Long return period rainfall. R&D Technical Report WS 194/2/39/TR (two volumes), Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme.
[4] ReFH2 Technical Guide https://refhdocs.hydrosolutions.co.uk

Section 4 presents the derivation of the initial conditions catchment descriptor equations, which were developed for the original ReFH2 design packages and implemented in ReFH2.1 and ReFH2.2. Within the ReFH2.3 design package, the user has the option to close the water balance over the event that is being modelled for the FEH13 DDF model. The revised rural C_{ini} models for the Water Balance design package option are presented in the 'ReFH2 Science Report: Closing a Water Balance' (2019)[5].

The ReFH2-FEH13 and ReFH2-FEH99 design packages use the same basic catchment descriptor parameter equations, but have different procedures for estimating model initial conditions. The FEH99 package includes another parameter which reduces the initial soil moisture condition with increasing event rarity. This hydrologically unattractive feature of the FEH99 design package is required to ensure a correspondence between the rainfall event return period and the corresponding flow event return period for this rainfall model. The legacy ReFH2-FEH99 design package using the original FEH99 DDF model[7] is summarised in 'ReFH2 Science Report: The ReFH2-FEH99 initial conditions and the alpha parameter' (2019)[8].

2 The ReFH Rural Model Components

A schematic of the ReFH rural model is presented in Figure 1. The rural model has three components: a loss model, a routing model and a base flow model.

The loss model uses a soil moisture accounting approach to define the amount of rainfall occurring over the catchment that is converted to nett rainfall. The rainfall losses are derived as the event unfolds, rather than being defined by a fixed value of percentage runoff. Nett rainfall is routed to the catchment outlet, the routing component of ReFH uses the instantaneous unit hydrograph concept, adopting a kinked triangle as the standard shape. Finally, the base flow model is based on the linear reservoir concept with its characteristic recession defined by an exponential decay controlled by the recession constant termed base flow lag. Drainage to baseflow is estimated indirectly from direct runoff, the rationale for this is discussed in the context of design application of the ReFH2 model.

The rural model has four model parameters and two model initial conditions which are presented in Table 1.

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[5] Wallingford Hydrosolutions 2019. ReFH2 Science Report: ReFH2 Science Report: Closing a Water Balance. Available via https://refhdocs.hydrosolutions.co.uk/References/.

[7] Faulkner, D.S. 1999 Rainfall Frequency Estimation. Volume 2 of the Flood Estimation Handbook, Centre for Ecology and Hydrology

[8] Wallingford Hydrosolutions 2019. ReFH2 Science Report: ReFH2 Science Report: The ReFH2-FEH99 initial conditions and the alpha parameter. Available via https://refhdocs.hydrosolutions.co.uk/References/.
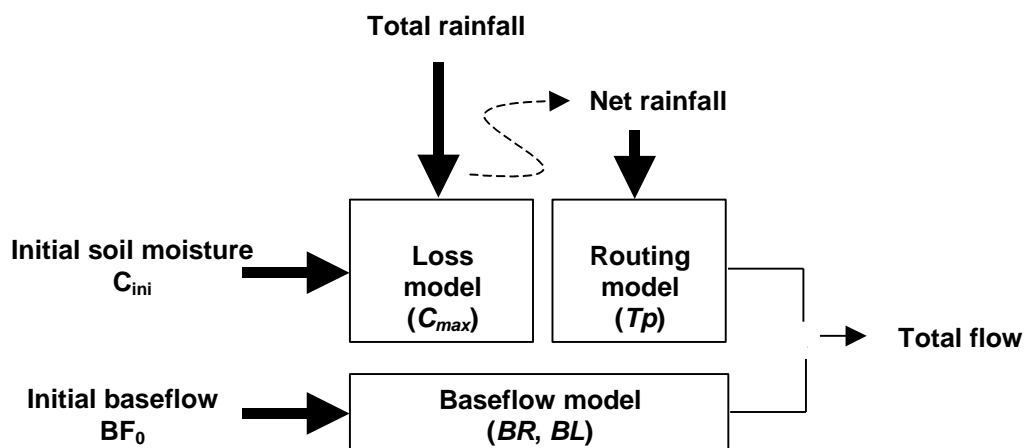
Figure 1. Schematic representation of the ReFH model

Table 1. Summary of the six ReFH model parameters

Name	Parameter or Initial Condition	Description
Tp	Model Parameter	Unit hydrograph time to peak (hours)
BL	Model Parameter	Baseflow recession constant or lag (hours)
BR	Model Parameter	Baseflow recharge
C_{max}	Model Parameter	Maximum soil moisture capacity (mm)
C_{ini}	Initial Condition	Initial moisture content (mm)
BF_0	Initial Condition	Initial baseflow (m^3s^{-1})

3 Estimating the ReFH2 Model Parameters for Ungauged Catchments

3.1 An overview

This section presents the derivation of relationships between the model parameters (Tp, C_{max}, BL and BR) and catchment descriptors to enable ReFH2 to be applied within a catchment without recourse to calibration. These model parameter catchment descriptor equations were developed for the original ReFH2 design packages and are implemented in ReFH2.1 and above (including the water balance version of the FEH13 design package implemented in ReFH2.3 where BFIHOST19 is used instead of BFIHOST). The relationships are constructed using regression modelling to explain the variation in calibrated model parameters within an appropriate sample of gauged catchments.

There are separate sets of parameter equations for Scotland and the other countries within the United Kingdom. The parameter equations for use within England, Wales and Northern Ireland are based upon a re-parameterisation of the relationships between the model parameters and catchment descriptors within the 101 catchments used within the original ReFH research[1]. A new set of parameter estimation equations were developed for Scotland[11]. The development work was undertaken in partnership with SEPA and predominantly used an extended set of calibration catchments within Scotland, although catchments from the north of England were also used in the development of the Tp equation.

To support the application of ReFH2 to drainage design, "plot scale" models have been developed for ReFH2 to estimate parameter values which use AREA as an alternative descriptor to DPLBAR and SAAR as an alternative to DPSBAR. Hence, ReFH2 can be used directly to estimate greenfield runoff rates and volumes at the plot scale.

The general form of the equations for estimating model parameters within the UK is shown in Table 2. The calibration of these equations is discussed in the following sections. Note that within the ReFH2.3 FEH13 design package the user has the option to close the water balance over the event that is being modelled. Dependent upon this user selection, BR will either be a model parameter, or an internal state variable that is set to ensure that the sum of the baseflow and direct runoff depths modelled for an event is equal to the rainfall depth in the event.

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[11] Wallingford Hydrosolutions 2019. ReFH2 Science Report: ReFH2 Science Report: Deriving ReFH catchment based parameter datasets in Scotland. Available via https://refhdocs.hydrosolutions.co.uk/References/.

Table 2. Structure of equations estimating ReFH 2 model parameters

ReFH parameter	Application	Parameter estimation equation
Tp	Catchment scale	$Tp = aPROPWET^{b}DPLBAR^{c}DPSBAR^{d}$
	Plot scale	$Tp = aPROPWET^{b}AREA^{c}SAAR^{d}$
C_{max}	Catchment and plot scale	$C_{MAX} = aPROPWET^{b}exp(cBFIHOST)$
BL	Catchment scale	$BL = aPROPWET^{b}DPLBAR^{c}BFIHOST^{d}$
	Plot scale	$BL = aPROPWET^{b}AREA^{c}BFIHOST^{d}$
BR	Catchment and plot scale	$BR = aPROPWET^{b}BFIHOST^{c}$

* Note that URBEXT2000 was included in the derivation of the equation coefficients for Tp and BL, but is not used in the estimation of the 'as rural' parameters as the influence of urban landuse on the flood hydrograph is incorporated explicitly within the ReFH2 urban model.

For all equations, the parameter is estimated as a product of the catchment descriptors. The equation coefficients are presented in ReFH2 in the context of application. For example, if a Scottish catchment is being the used, the model coefficients are those for the Scotland parameter equations. Similarly, if the plot scale equations are being used the structure and coefficients presented are for the relevant plot scale equations.

The sensitively of a parameter to the value of the catchment descriptors used is best illustrated by considering the magnitude of the individual equation components to the value of the catchment descriptor. These are graphed over the normal range of catchment descriptor values for both sets of ReFH2.1 and above catchment scale parameter equations within Figure 2 and Figure 3. The catchment descriptors are described in detail within the Flood Estimation Handbook Volume 5[12].

Considering the Time to Peak (Tp), it can be seen that the dependency on PROPWET (a measure of the fraction of time the catchment is wet) is similar for both parameter sets with the estimate of Tp being particularly sensitive to PROPWET within drier catchments. In contrast, the estimation of Tp is very sensitive to the scale of the catchment (DPLBAR) in England, Wales and Northern Ireland and less so in Scotland. In Scotland, Tp is generally more influenced by the gradients of drainage paths within catchments and is more sensitive to those gradients. The higher scale dependency in England, Wales and Northern Ireland is strongly influenced by the larger, relatively dry catchments within the ReFH calibration dataset. In the generally wetter Scottish context this is not observed and gradient is a stronger discriminating descriptor.

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[12] Bayliss A, 1999. Catchment Descriptors. Volume 5 of the Flood Estimation Handbook. Centre for Ecology and Hydrology.

A key catchment descriptor within the original ReFH1 research for explaining the variability in model parameter estimates is the estimate of the Base Flow Index (BFI) based on Hydrology of Soil Types (HOST)[13], the BFIHOST. The BFIHOST is estimated using a regression model that explains the variability in BFI values across gauged catchments within Great Britain, which was developed as a classification tool.

BFIHOST and PROPWET are partially covariant across the remainder of the UK, with the permeable aquifer outcrops being located in drier areas and with the soils also tending to be more permeable in these outcrop areas. The "mirror image" differences in the dependency on PROPWET and BFIHOST in the estimation of BL is a consequence of the relatively small range of BFIHOST (tending towards impermeable) observed in Scotland resulting in PROPWET being a stronger discriminatory descriptor. In contrast, across the remainder of the UK, the dependency on climate and soils and geology is, in the main captured by the variation in BFIHOST, with BFIHOST describing the influence of soils and geology and as a surrogate for the climate dependency. In contrast the patterns in the dependency of BR on PROPWET and BFIHOST are very similar. However, C_{max} is more sensitive to PROPWET in Scotland and less sensitive to BFIHOST, again a reflection in the relative variation in the descriptors across the UK.

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[13] Boorman, D.B., Hollis, J.M. and Lilly, A. 1994. Hydrology of Soil Types: a Hydrologically-based Classification of the Soils of the United Kingdom. IH Report 126.
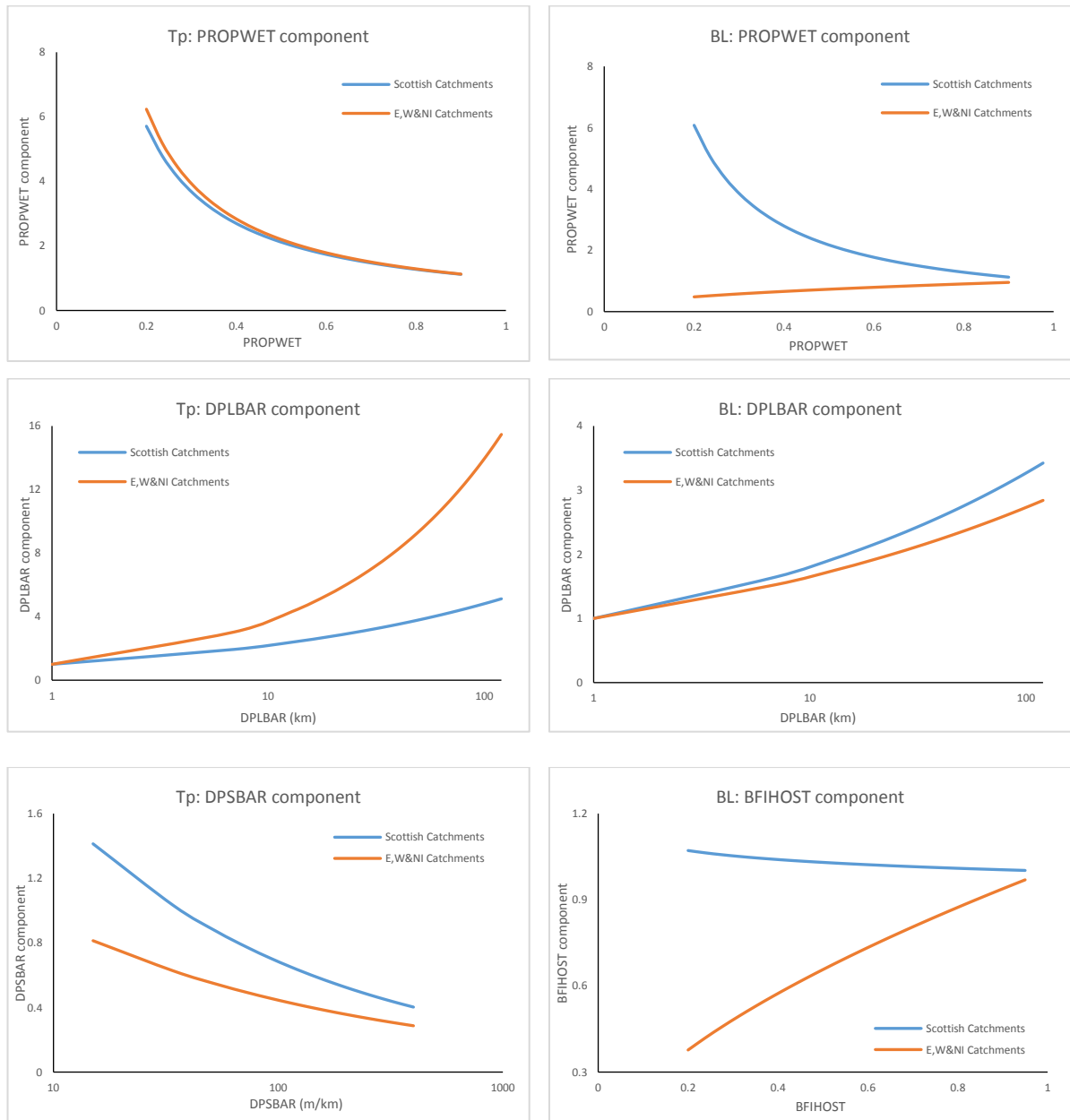
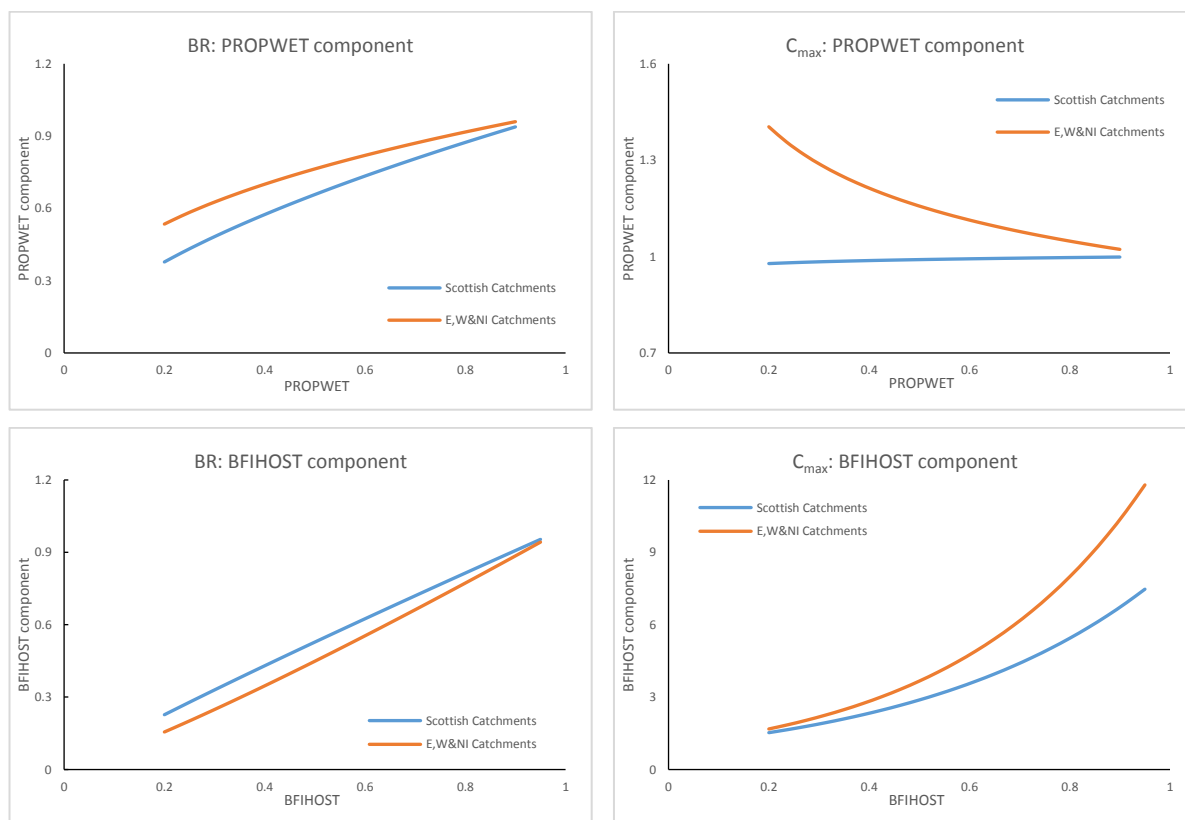Figure 2 Catchment descriptor dependencies for Tp and BL

Figure 3 Catchment descriptor dependencies for BR and C_{max}

3.2 Parameter estimation equations for use in Scotland

The selection and calibration of ReFH within catchments across Scotland is discussed in the 'ReFH2 Science Report: ReFH2 Science Report: Deriving ReFH catchment based parameter datasets in Scotland' (2019)[11]. This yields a set of 19 calibrated model parameter sets to form the basis of the parameter estimation equations for application in Scotland.

Due to the nature of the soils, geology and topography, BFI values estimated from gauged records within Scotland are generally biased towards lower values. Research underpinning the development of the LowFlows software within Scotland[15], identified a systematic bias towards over prediction of BFI when using the BFIHOST model. As part of this research, a Scotland specific model for estimating BFI was developed (the BFIScot model). The model provides an improved estimate of BFI in Scotland, particularly within low BFI catchments.

The new BFIHOST19 is used instead of BFIHOST within the water balance version of the FEH13 design package implemented in ReFH2.3 as presented in 'ReFH2 Science Report: Closing a Water Balance' (2019)[5].

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[15] www.sepa.org.uk/science_and_research/idoc.ashx?docid=afb95859-0f25-4827-9210-411d2fae48ac&version = -1

Equations to estimate the four ReFH model parameters, Tp, C_{max}, BL and BR, from catchment descriptors were developed for both catchment and plot scale application using the calibration data set of 19 Scottish catchments.

A searching algorithm that tests the explanatory power of all potential independent variables was used to ascertain the structure and parameterisation of the optimal regression model. The method used the parameters estimated from the calibration data to derive the equation; the parameter for each gauging station was weighted according to the number of events associated with the gauging station. Note that the Dargall Lane at Loch Dee Lane (80005) was not included within the estimation of C_{max}. This was a significant outlier within the data set which exhibited an atypical relationship between BFI and C_{max}.

Measures of predictive performance of the equations for estimating C_{max}, Tp, BL and BR are presented in Table 3 and illustrated in Figure 4 to Figure 7. These figures also illustrate the marginal benefit of using the Scotland specific BFIScot variable rather than BFIHOST. The plot scale equations for Tp and BL perform similarly to the catchment scale equations and hence confirm that the ReFH2 models are suitable for application at the plot scale. Use of methods identifies issues and following feedback from the Scottish Environment Protection Agency on the performance of ReFH2.0 and ReFH2.1, it was identified that the Scottish Tp equation tended to be underestimated in drier catchments towards the eastern coast of Scotland. This led to the development of a revised parameter equation for Tp using a larger dataset drawing from the calibrated catchments used in the original ReFH development work in the north of England. This revision of Tp for use in Scotland is presented in the 'ReFH2 Science Report: ReFH2 Science Report: Deriving ReFH catchment based parameter datasets in Scotland' (2019)[11].

Table 3. Performance of equations for estimating ReFH model parameters in Scottish catchments

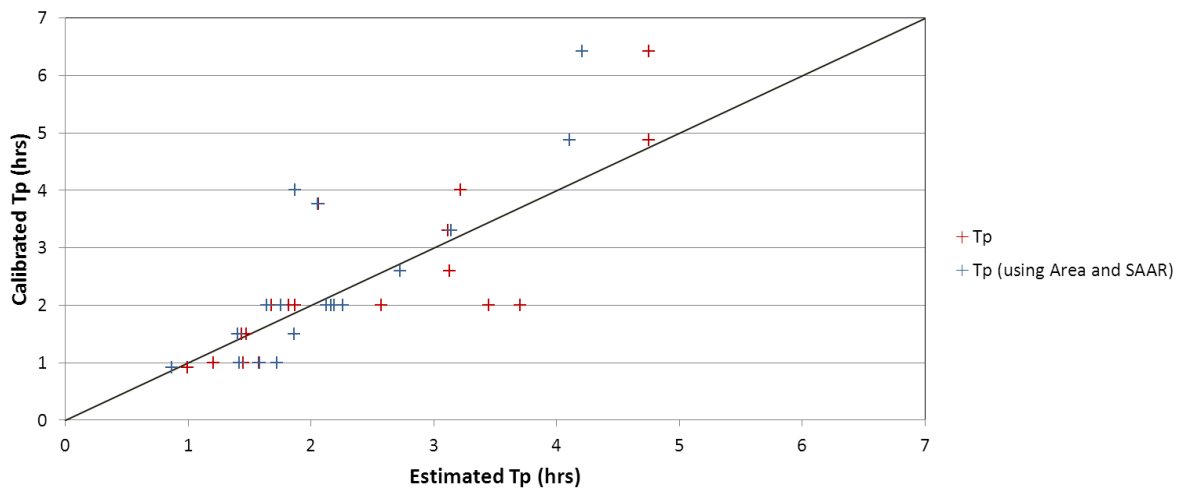| ReFH parameter	Application	R^2	Factorial Standard Error
Tp	Catchment scale	0.68	1.37
	Plot scale	0.73	1.4
C_{max}	Catchment and plot scale	0.57	1.15
BL	Catchment scale	0.72	1.2
	Plot scale	0.73	1.2
BR	Catchment and plot scale	0.22	1.4

Figure 4. Calibrated and estimated Tp: blue symbols are the catchment parameter equation results and the red symbols those for the plot scale parameter equation estimates
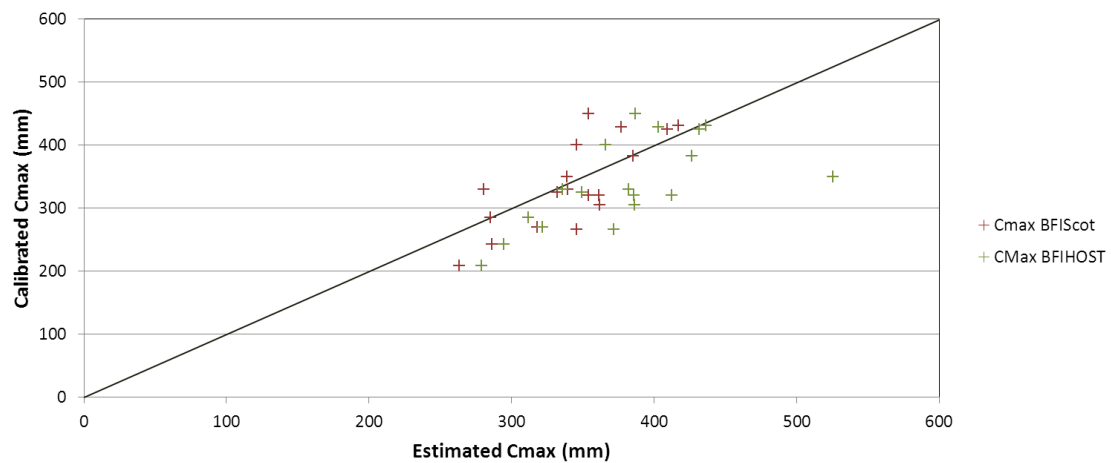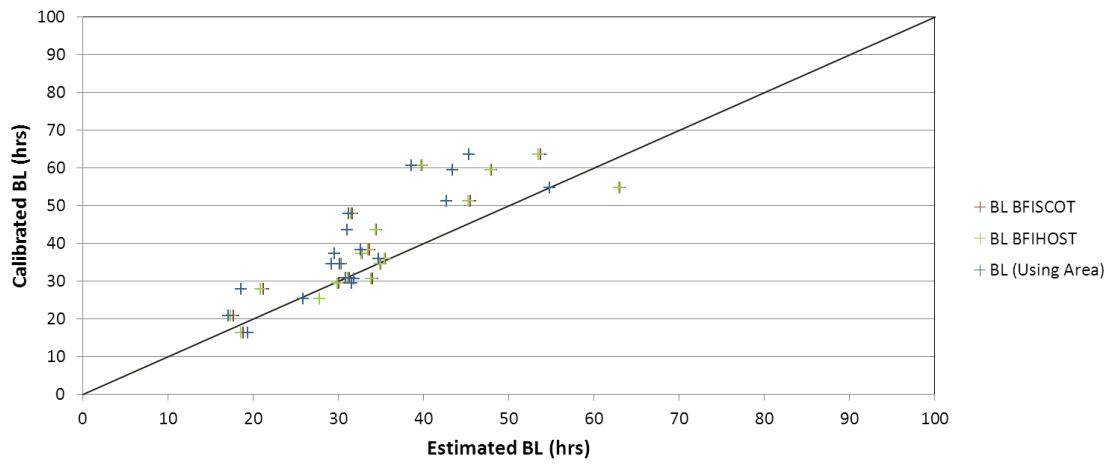

Figure 5. Calibrated and estimated C_{max}

Figure 6. Calibrated and estimated B_L
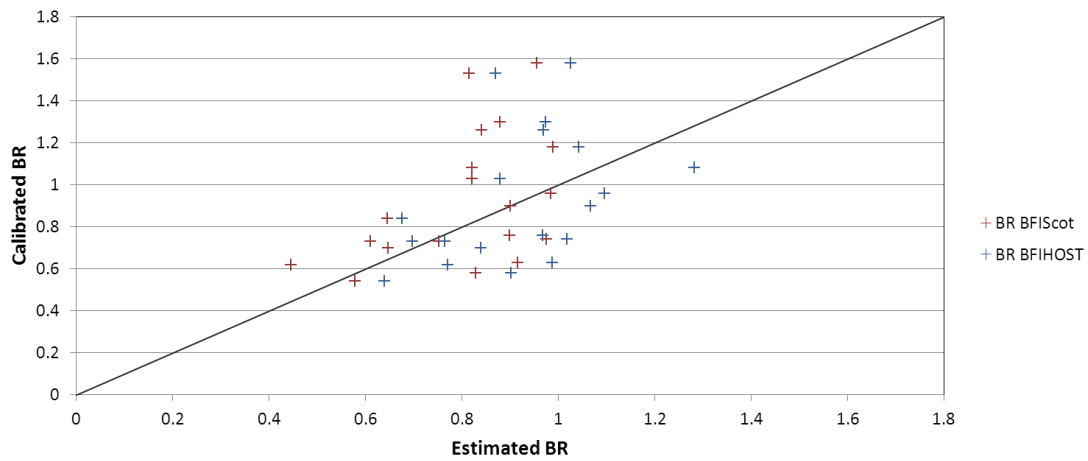

Figure 7. Calibrated and estimated B_R: blue symbols are the catchment parameter equation results and the red symbols those for the plot scale parameter equation estimates.

3.3 Parameter estimation equations for use in England, Wales and Northern Ireland

Equations to estimate the four main model parameters Tp, C_{max}, BL and BR were developed using the searching algorithm described within the previous sub-section and a base data set of the 101 calibration catchments developed for the original ReFH1 research. This catchment dataset is presented in full by Kjeldsen et al. (2005)[16]. Both catchment and plot scale formulations of the equations for Tp and BL were developed.

The predictive performance of the equations for estimating Tp, C_{max}, BL and BR is summarised in Table 4 for catchment and plot scale applications. Illustrations of model performance are shown on Figure 8 to Figure 11.

The new equations significantly reduce the factorial standard errors for estimation of parameters. The alternative plot scale equations for Tp and BL indicate that there is little loss in performance, thus allow the models to be used at the plot scale.

BFIHOST19 is used instead of BFIHOST within the water balance version of the FEH13 design package implemented in ReFH2.3 as presented in 'ReFH2 Science Report: Closing a Water Balance' (2019)[5].

Table 4. Performance of equations for estimating ReFH model parameters in catchments in England, Wales and Northern Ireland

ReFH parameter	Application	R^2	Factorial Standard Error
Tp	Catchment scale	0.80	1.3
	Plot scale	0.71	1.36
C_{max}	Catchment and plot scale	0.6	1.29
BL	Catchment scale	0.35	1.49
	Plot scale	0.31	1.48
BR	Catchment and plot scale	0.36	1.51

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[16] T.R. Kjeldsen, E.J. Stewart, J.C. Packman, S.S. Folwell & A.C. Bayliss, 2005. Revitalisation of the FSR/FEH rainfall-runoff method. Defra R&D Technical Report FD1913/TR
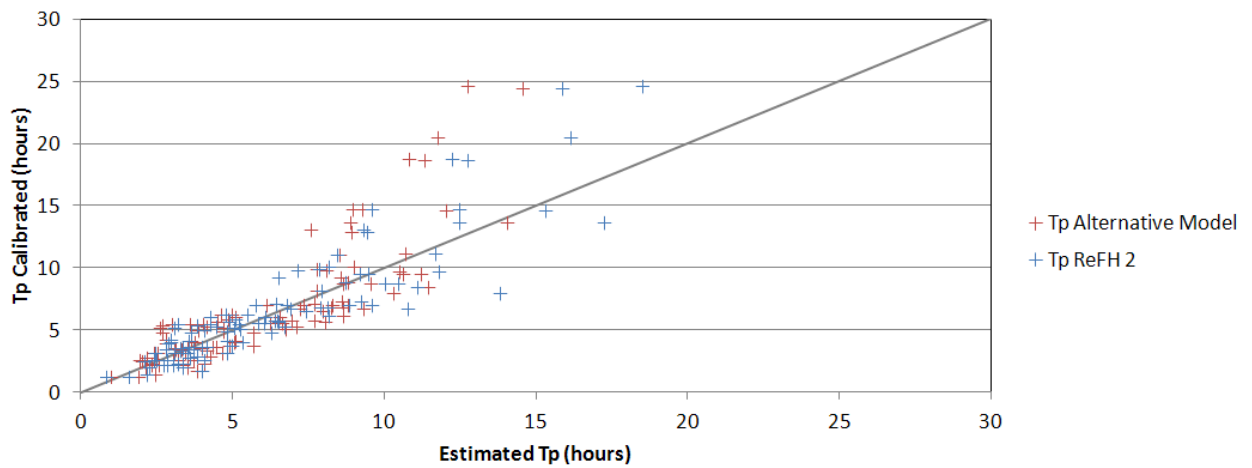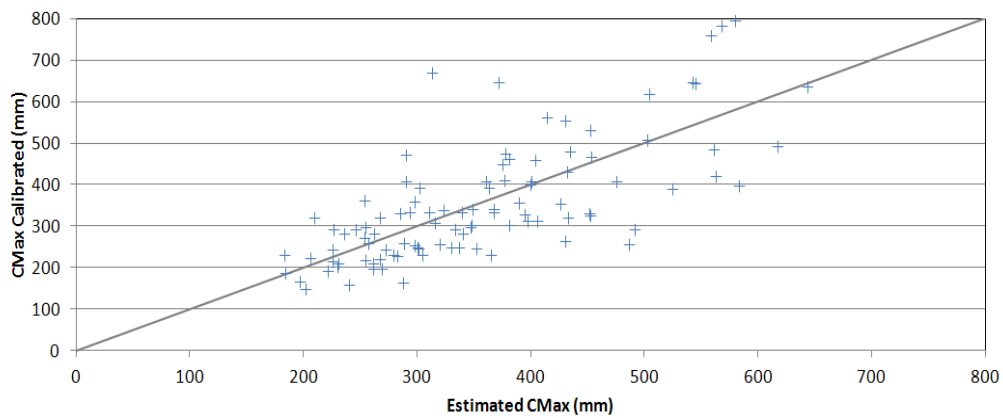
Figure 8. Calibrated and estimated Tp

Figure 9. Calibrated and estimated C_{max}

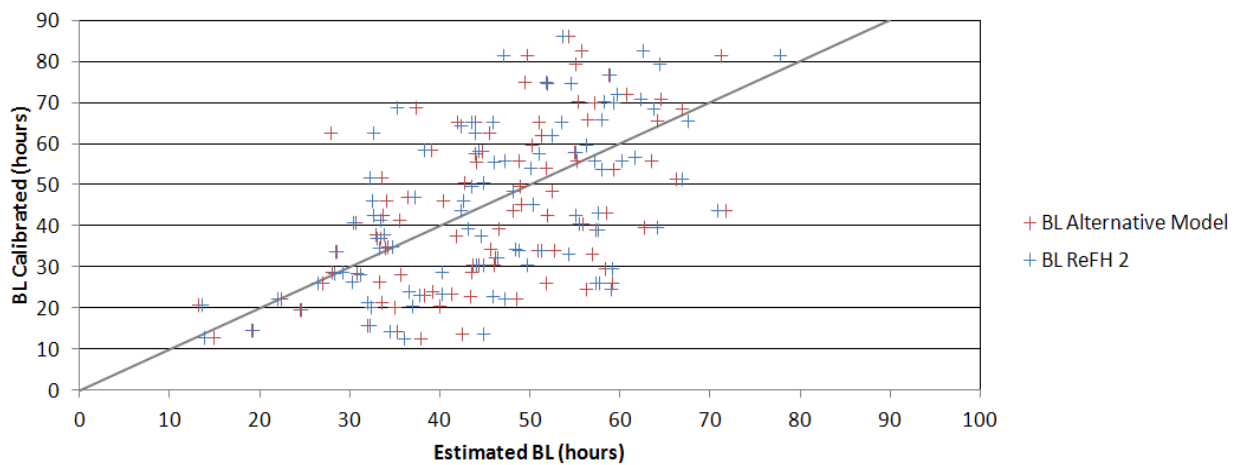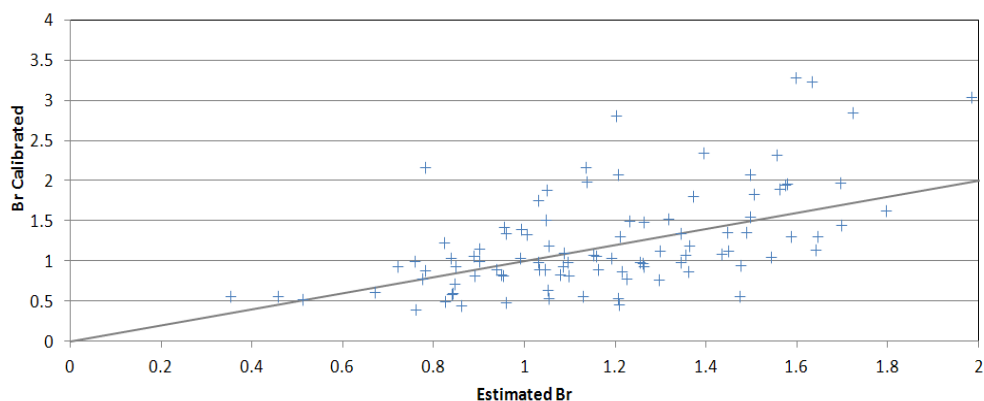Figure 10. Calibrated and estimated BL

Figure 11. Calibrated and estimated BR

4   Estimating the Design Initial Conditions

4.1   Estimation of the initial soil moisture C_{ini}

4.1.1   Overview

The estimation of the initial depth of water held in storage (C_{ini}) in the catchment is a key component of the ReFH design package. For a given set of model parameters and rainfall event, a low C_{ini} results in a hydrograph with a smaller runoff volume and hence peak flows; conversely if C_{ini} is high, the hydrograph runoff volume and peak flow will be higher. This section presents the derivation of the C_{ini} estimate implemented within the ReFH2.2 model. The revised rural C_{ini} models for the ReFH2.3 Water Balance design package option are presented in the 'ReFH2 Science Report: Closing a Water Balance' (2019)[5].

Analysis of the seasonality of annual maxima has shown that large events in the annual maximum flood series (AMAX) are dominated by winter storms in rural catchments. This is a consequence of both the dominance of large winter storms associated with Atlantic depressions along the west and north of the UK and the fact that winter evaporation rates are low and hence soils moisture deficit are low or negligible. The signal of higher winter precipitation is less pronounced in the rain shadowed east of the UK with convective storms featuring in the larger storm series. However, the influence of low summer rainfall and higher evaporation demand means that summer soil moisture deficits in eastern and southern catchments tend to be higher than their western and northern counterparts. Hence winter storms still dominate the AMAX series in these areas of the UK. In contrast, in heavily urbanised catchments with extensive and commonly positively drained impervious surfaces, the largest floods can commonly be as a result of large convective summer storms.

The original ReFH2-FEH13 package implemented within the ReFH2.2 model facilitates the estimation of the hydrograph and hence peak flow corresponding to a winter storms through the provision of a model for estimating winter C_{ini}. Under recent Environment Agency funded research on small catchment flood estimation[17] (Report 6) the seasonality of the AMAX series was re-evaluated for all catchments on the NRFA Peak Flows data set and small catchments of less than 40km^2. The small catchments dataset was comprised of the catchments within the NFRA Peak Flows data set that met this size criterion augmented by an additional set of small catchments collated for the project.

This research extended the ReFH2-FEH13 design package functionality by developing a procedure for estimating an as rural summer C_{ini} model for application in conjunction with an FEH13 based summer design hyetograph. This has been implemented within the ReFH2.3 software for both the ReFH2.2 and ReFH2.3 models. The derivation of design summer hyetographs is summarised in the ReFH2 Technical Guide[4] with supporting literature referenced. The development of the winter C_{ini} and the summer C_{ini} is presented within this report. Further detail on the analysis of storm seasonality and the detail of the development of the summer C_{ini} model is provided by the EA Small Catchments Project Report 6[17].

4.1.2   Estimation of the Winter C_{ini}

The spatial patterns in the differences between the FEH13 and FEH99 rainfall models and how these vary as a function of return period are discussed within the ReFH2 Technical Guide[4] with supporting literature referenced. These differences warranted the development of a new winter C_{ini} model.

The legacy FEH99 C_{ini} model and the attendant Alpha parameter is presented in detail within 'ReFH2 Science Report: The ReFH2-FEH99 initial conditions and the alpha parameter' (2019)[8]. Alpha is a factor applied to C_{ini} to compensate for bias in the FEH99 rainfall model in climatically wetter catchments and for longer return period events by reducing C_{ini}. Calibrated against estimates from the FEH statistical method, Alpha ensures a correspondence between rainfall event frequency and the frequency of the estimated peak flow. Alpha is both hydrologically counter-intuitive and as it was calibrated using FEH statistical estimates it had the other unattractive outcome that the ReFH2-FEH99 estimates of peak flow are not independent of the corresponding statistical estimates. These same criticisms applied to the original ReFH research and ReFH1 software.

As a consequence of the relative differences between the FEH13 and FEH99 rainfall models, an alpha parameter is not required for the ReFH2-FEH13 design package, addressing previous criticisms of the parameter.

Inspection of the magnitude of calibrated events in the original 101 catchment dataset and the additional catchments for Scotland introduced for the ReFH2 research identified that there is no significant relationship between the C_{ini} and the magnitude of the event.

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[17] Environment Agency, Estimating flood peaks and hydrographs for small catchments: Phase 2, Project: SC090031, *Not yet published*

The ReFH2-FEH13 C_{ini} model was developed based on the estimation of the 1:2 Annual Exceedence Probability C_{ini}. The approach adopted considered a subset of the NRFA Peak Flow Dataset 3.3.4 was used for the analysis. The set selected used catchments flagged as:

● appropriate for the calculation of QMED,
● with more than 14 years of data (recommended for the calculation of QMED[18]),
● essentially rural (URBEXT2000<0.03); and
● as the impact of flood attenuation by reservoirs and lakes is not included within the ReFH model structure catchments with FARL<0.9 were also removed from the dataset.

The final dataset had 546 stations. The following process was applied to each catchment:

● The 1:2 AEP design storm was estimated using the FEH13 DDF model in conjunction with the recommended duration for the catchment.
● The ReFH2 model was run with design package parameter estimate and the design package estimate of the BF_0 initial condition.
● The value of C_{ini}/C_{max}, range [0,1] required to calibrate the ReFH2 estimate of the median annual peak flow, QMED, to the value of QMED estimated directly from the gauged record was identified.

From this catchment dataset 15 catchments were excluded for water balance violations. These were identified as catchments for which both the ReFH optimal QMED estimate and FEH QMED catchment descriptor equation overestimated the QMED from the AMAX series by more than factor 3 or under-estimated by factor 0.33. As a secondary check a comparison with a water balance estimate of gauged and mean flow estimated using the runoff grid method implemented within the LowFlows software (Holmes et al, 2002[19]) was also made. If this estimate was also in error, and in the same direction as the QMED estimates errors the catchment was rejected on water balance considerations. This reduced the catchment data set to 531 catchments.

QMED was selected for this work as it can be directly estimated from gauged AMAX data and the RMED magnitude is also encapsulated within the rainfall records underpinning the DDF model. The model parameters equations are also based on calibration results for observed events. Thus, this approach to calibrating the 1:2 AEP C_{ini} model can be regarded as akin to a calibration against observed data.

The optimised values were used to develop a generalised equation for the estimation of the normalised C_{ini} (defined as the ratio of C_{ini} to C_{max}). A linear relationship between the logarithms of the normalised C_{ini} and BFIHOST provided the best fit for the data. The form of this relationship is:

Equation 1

$$ln\left(\frac{Cini}{Cmax}\right) = a \,.\, BFIHOST + b$$

The relationship between modelled C_{ini}/C_{max} and BFIHOST is presented in Figure 12.

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[18] Robson A & Reed D, 1999. Statistical procedures for flood frequency estimation, Flood Estimation Handbook Volume 3.
[19] Holmes, M.G.R., Young, A.R., Gustard, A.G. and Grew, R. 2002. A new approach to estimating Mean Flow in the United Kingdom. Hydrology and Earth System Sciences. 6(4) 709-720.
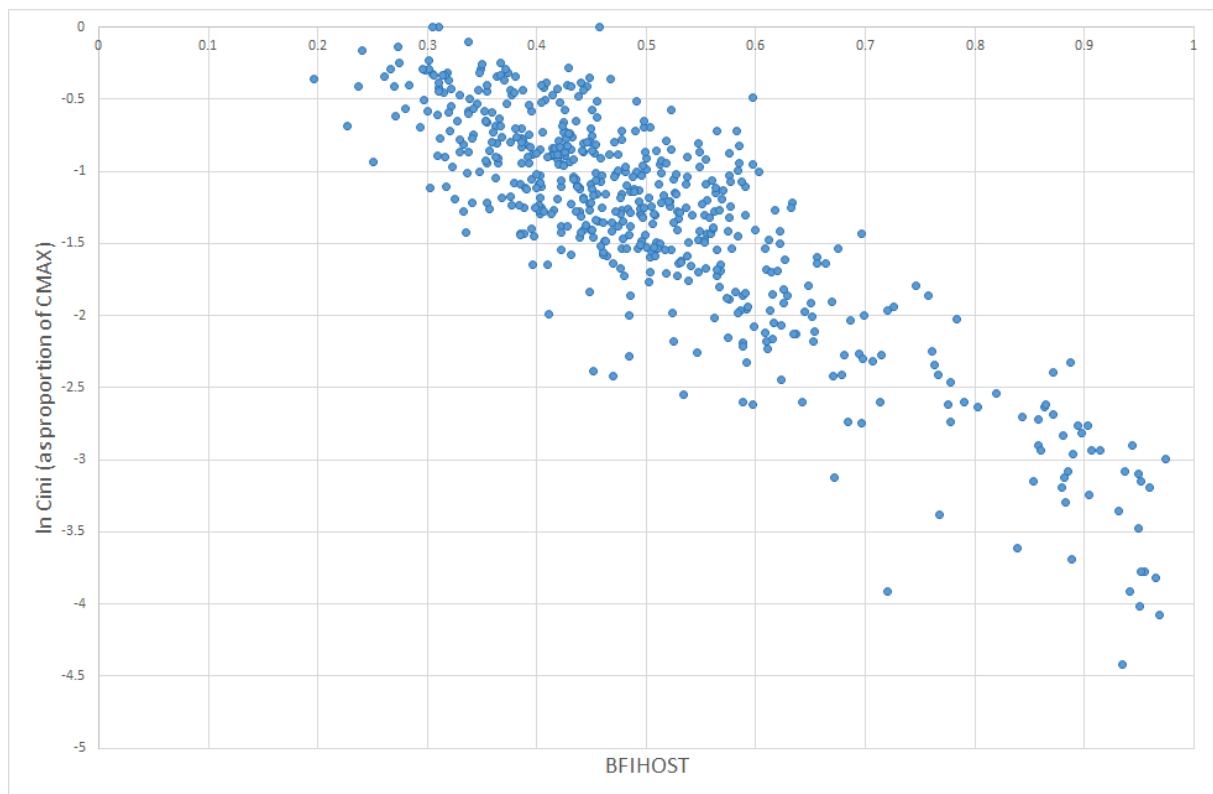
Figure 12 The relationship between the optimal C_{ini} and the BFIHOST value for stations from the NRFA Peak Flows dataset flagged as being suitable for Q_{MED} estimation.

4.1.3   Estimation of the Summer C_{ini}

The development of the summer C_{ini} model is summarised below and presented in full in EA Small Catchments Project Report 6[17]. Within this research the C_{ini} calibration procedure used for the winter storm was repeated for the summer storm (summer seasonal correction factor) and using both the winter and summer storm profiles. Results obtained using the two storm profiles were evaluated as there is an industry perception that the summer profile may be too peaked.

Figure 13 presents these relationships for the full summer design model and winter profile design model. The form of the relationships are described by Equation 2 with the gradients, intercepts and measures of fit summarised on Table 5.

Equation 2

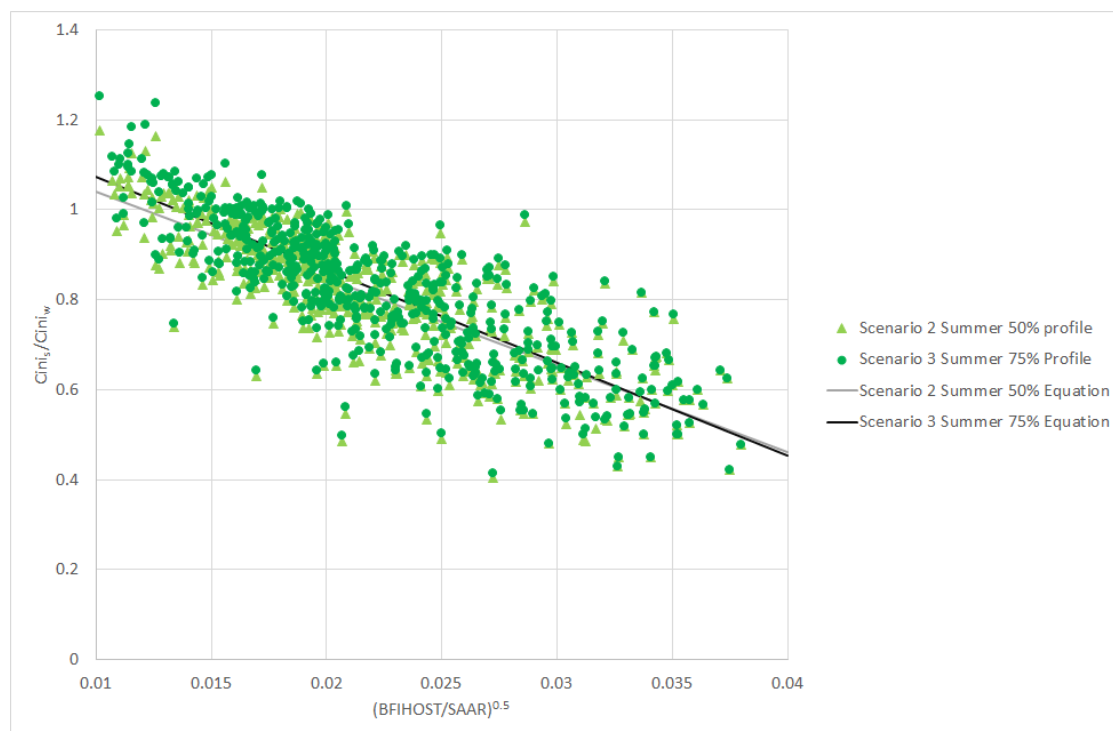$$\frac{C_{iniS}}{C_{iniW}} = m \left(\frac{BFIHOST}{SAAR} \right)^{0.5} + c$$

Figure 13   The relationships between summer and winter C_{ini} and the ratio of *BFIHOST* to *SAAR* for summer storms with summer profiles and summer storms with winter profiles

Table 5   Model parameters and fit statistics for estimating summer C_{ini} from the Design winter C_{ini}

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

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

Only the full summer storm (Summer SCF, 50% summer profile) C_{ini} has been implemented within ReFH2.3.
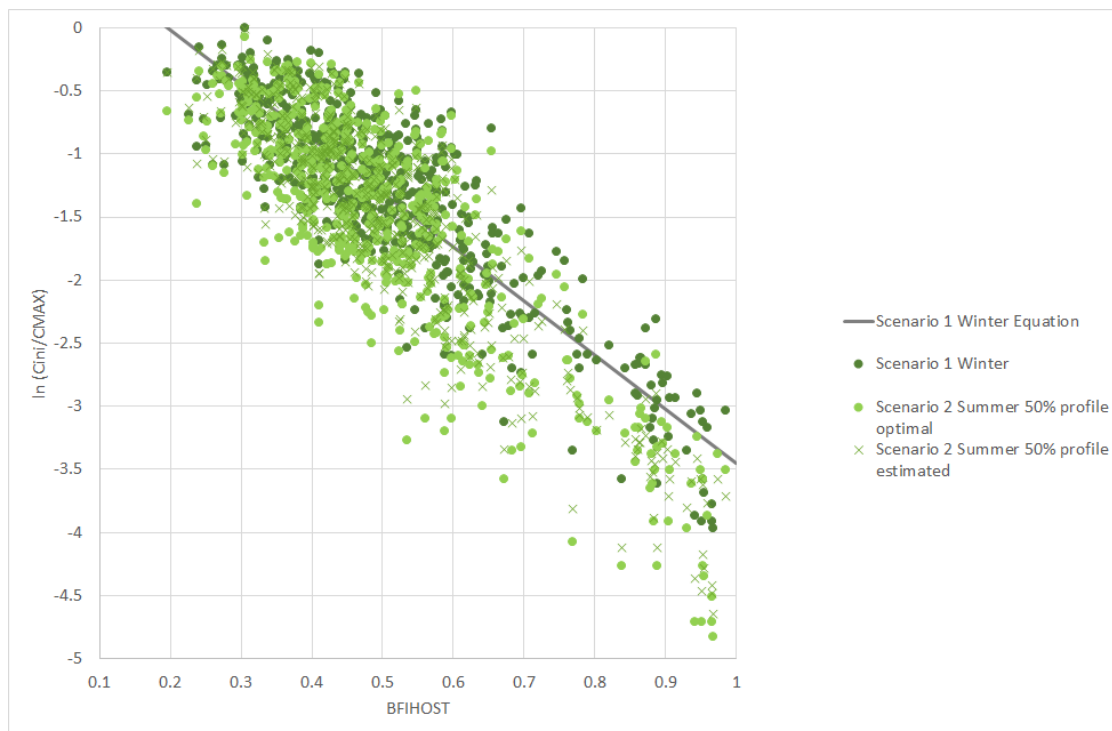
Figure 14   Models for estimating design winter and summer C_{ini}/C_{max} values as a function of BFIHOST for the winter and Scenario 2: summer conditions used in conjunction with the 50% summer profile.
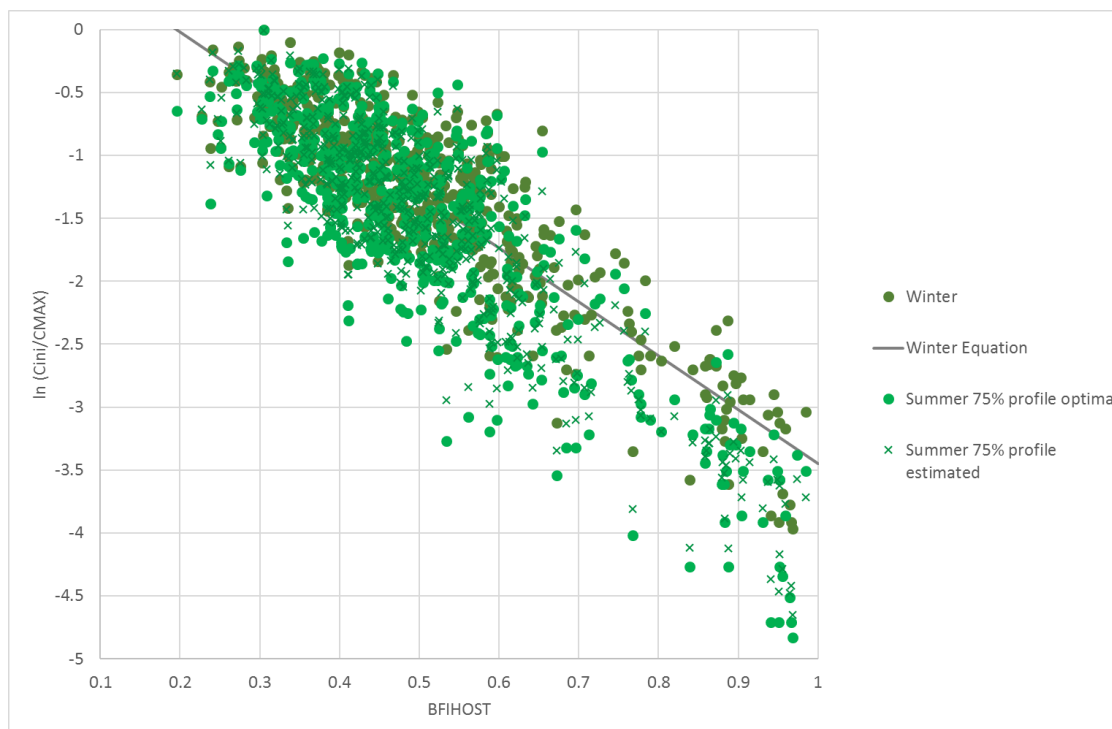

Figure 15   Models for estimating design winter and summer C_{ini}/C_{max} values as a function of *BFIHOST* for the winter and Scenario 3: summer conditions used in conjunction with the 75% winter profile.

4.2 Estimation of BF_0

Summer and winter estimates of BF_0 are required for use with the summer and winter design storms (and corresponding values of C_{ini}). The original ReFH BF_0 equations developed by Kjeldsen et al. 2005 were adopted for use within ReFH2 for England, Wales and Northern Ireland. Revised BF_0 equations were developed for Scotland using the same approach but focused on the catchments used for calibration of ReFH2 within Scotland. These have been implemented within ReFH2.1 and above. The equations are as follows:

England, Wales and Northern Ireland

$$BF_{0,winter} = (63.8(C_{ini} - 120.8) + 5.54 SAAR)10^{-5} AREA$$

$$BF_{0,summer} = (33.9(C_{ini} - 85.4) + 3.14 SAAR)10^{-5} AREA$$

Scotland

$$BF_{0,winter} = (49.6(C_{ini} - 119.8) + 3.88 SAAR)10^{-5} AREA$$

$$BF_{0,summer} = (-49.8(C_{ini} - 112.8) + 2.95 SAAR)10^{-5} AREA$$