ReFH2 Science Report

Deriving ReFH catchment based parameter datasets in Scotland

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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.

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.

This Science Report presents the selection and calibration of ReFH within catchments across Scotland. The development work was undertaken in partnership with Scottish Environment Protection Agency (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. This analysis was published within the ReFH2.2 Technical Guidance[3] in 2016 and is republished within this Science Report as supporting documentation for ReFH2.3.

Section 2 presents the collation and summary of the Scotland dataset, with the model calibration presented in Section 3.

Following the releases of versions 2.0 and 2.1 of the ReFH2 software, SEPA identified that the Scotland Time to Peak (Tp) estimates were smaller (resulting in shorter recommended duration events) and particularly so in larger, drier catchments when compared those of ReFH1 and the FSR rainfall runoff model. Section 4 presents the increased sample set of catchments for derivation of an improved Time to Peak Tp parameter for implemented within Scotland within for ReFH2.2 and above.

[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] Wallingford Hydrosolutions 2016. The Revitalised Flood Hydrograph Model ReFH2.2 Technical Guidance.

2 Collation and Summary of Scotland Dataset

2.1 Catchment Selection

To provide a source of flow events for calibration, a dataset of tipping bucket precipitation and 15 minute flow data was compiled for 28 gauging stations across Scotland by SEPA. The calibration of ReFH within a catchment also requires antecedent soil moisture conditions to be estimated using a daily soil moisture accounting procedure. The inputs for this procedure are catchment average time series of rainfall and Potential Evaporation (PE) series. The gridded climate products developed as part of the research underpinning the daily time step generalised Continuous Estimation of River Flows (CERF[4]) rainfall runoff model were used for this purpose.

Of the initial dataset of 28 gauging stations proposed, a total of 19 gauging stations were verified for use within the project. The gauging stations, together with reasons for inclusion or exclusion, are listed within Table 1 and presented within Figure 1. If the FEH FARL (Flood Attenuation by Reservoir and Lakes) was less than 0.90 the station was excluded - the storage within the loch would affect the calibration of the model as there is no process representation of open water bodies within the ReFH model. The Lossie at Sheriffmills (NRFA ID 7003) was removed during the calibration process due to unsatisfactory model calibrations. Discussions with SEPA (pers. comms[5]) concluded that it was likely that the rainfall data available for this catchment may not be representative of the weather patterns that drive higher flow events within this catchment.

Table 1. Gauging Stations considered for use within the ReFH calibration for Scotland.

Accept or reason for rejection	NRFA ID	Catchment	AREA	No. Years of Rainfall and Flow Data
FARL	1001	Wick at Tarroul	158.18	9
FARL	2002	Brora at Bruachrobie	423.64	6
Data	3002	Carron at Sgodachail	236.58	0
Accept	7001	Findhorn at Shenachie	415.73	21
Accept	7002	Findhorn at Forres	781.69	21
Water Balance	7003	Lossie at Sheriffmills	216.66	8
Accept	7005	Divie at Dunphail	164.63	17
Accept	8004	Avon at Delnashaugh	540.58	11
Accept	8009	Dulnain at Balnaan	272.2	13
Accept	8013	Feshie at Feshiebridge	229.63	10
Accept	9001	Deveron at Avochie	444.84	9
Accept	9002	Deveron at Muirsk	961.44	9
Data	9003	Isla at Grange	180.01	0

[4] Griffiths, J., Keller, V., Morris, D., Young, A.R., 2008. Continuous Estimation of River Flows (CERF). Science Report SC030240. Environment Agency.
[5] Personal Communication, Alistair Cargill, 2013, SEPA.

Accept or reason for rejection	NRFA ID	Catchment	AREA	No. Years of Rainfall and Flow Data
Accept	12006	Gairn at Invergairn	145.91	4
Accept	12008	Feugh at Heughhead	232.84	16
Accept	13004	Prosen Water at Prosen Bridge	107.6	14
Accept	15015	Almond at Newton Bridge	83.97	12
Accept	16003	Ruchill Water at Cultybraggan	1.85	15
Accept	77004	Kirtle Water at Mossknowe	69.93	15
Accept	79004	Scar Water at Capenoch	142.76	18
Accept	80003	White Laggan Burn at Loch Dee	5.74	18
Accept	80005	Dargall Lane at Loch Dee	2.07	19
Accept	84030	White Cart Water at Overlee	106.42	15
Data	86001	Little Eachaig at Dalinlongart	31.85	0
FARL	92001	Shiel at Shielfoot	255.12	11
Accept	96001	Halladale at Halladale	193.72	11
FARL	96002	Naver at Apigill	474.05	16
FARL	96003	Strathy at Streathy Bridge	120.89	7

Figure 1 illustrates the location of the gauging stations within the calibration dataset. This shows that the catchment data set are biased towards the east of Scotland. This reflects both the relatively low gauging station density within the Highlands and the fact that the gauged catchments within this area tend to include large lochs.

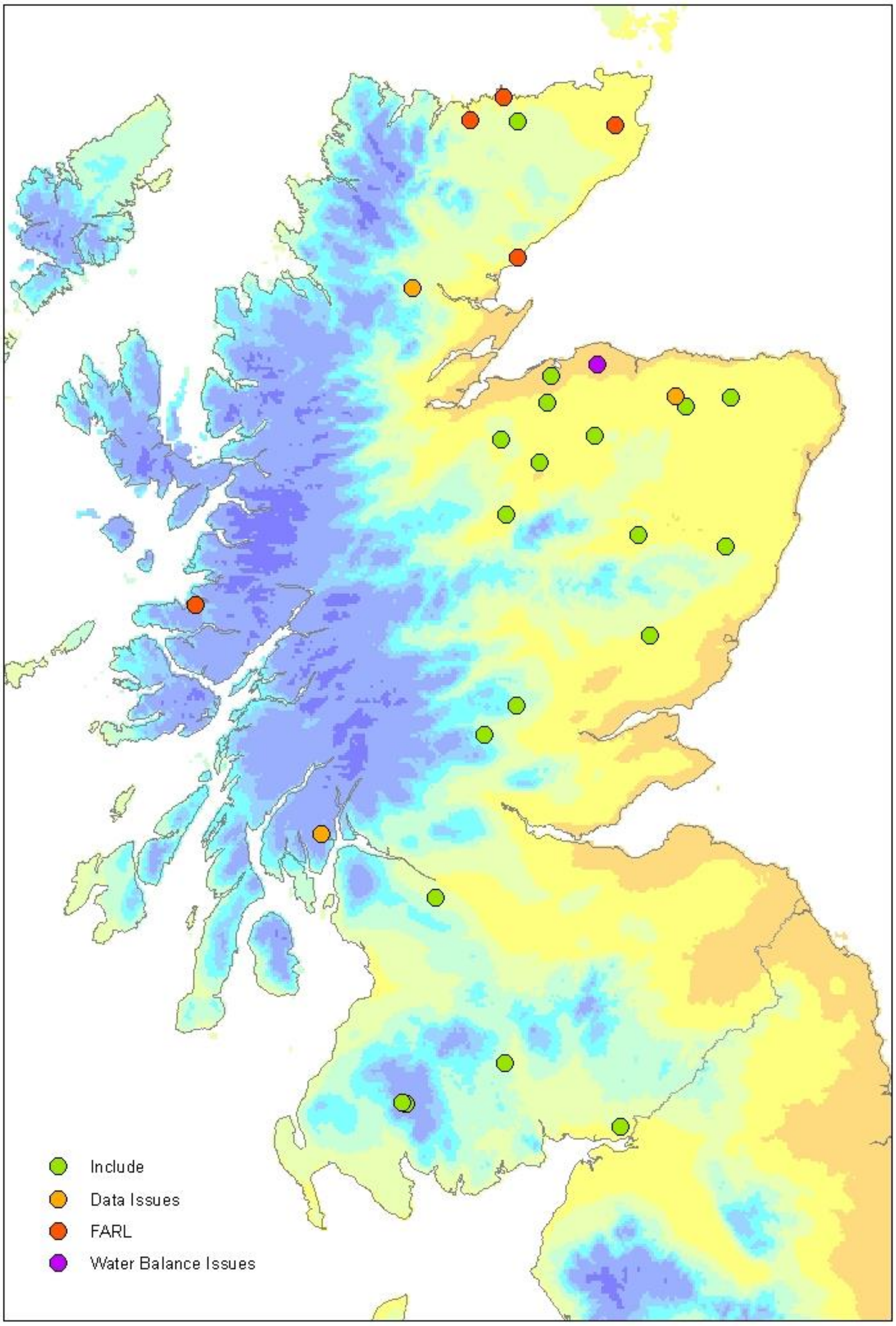

Figure 1. Location of Scottish gauging stations used within the ReFH calibration for Scotland.

Figure 2 presents the distribution of the catchment descriptors for the calibration dataset compared with those for the entire Scottish river network (where catchment area >0.5km²). This illustrates that the calibration dataset is dominated by BFIHOST values in the range 0.3 to 0.6 and the extremes of the distribution not well represented. The range of catchment areas and DPLBAR (mean drainage path length) calibration dataset is large, hence the calibration data set includes both small and large catchments. The variability of SAAR (standard-period average annual runoff) and DPSBAR (mean drainage path slope) is fairly well represented, but the dataset is slightly biased towards mid-range values of PROPWET values (proportion of time when SMD was less than or equal to 6mm during the period 1961-90).

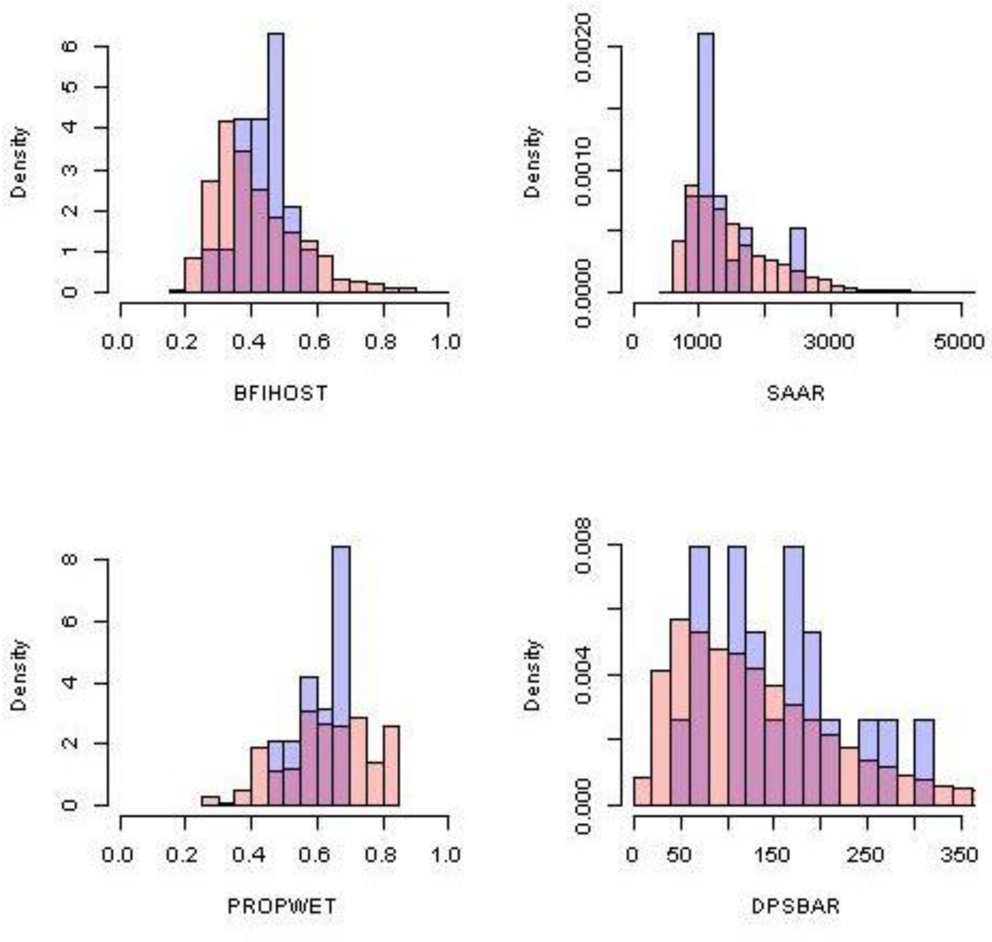

Figure 2. The distribution of the dominant catchment descriptors for the calibration dataset and all sites on the river network greater than 0.5km² within Scotland (FEH CD ROM dataset). The Scottish calibration dataset is blue, whilst the Scottish river network is red. Note that Area and DPLBAR are not presented as, in using the entire river network, these are dominated by very low values thus do not provide information on the validity of the calibration dataset.

Figure 3 presents the distribution of the catchment descriptors of most relevance to the ReFH model from the Scottish calibration dataset compared with the original ReFH calibration dataset. The Scottish dataset includes a number of stations greater than the maximum of 510km^2 used in the original calibration dataset; The Findhorn at Forres (7002) is 782km^2 and Deveron at Muirsk (9002) is 961km^2. There are also two catchments under 5km^2; Ruchill Water at Culty Braggan (16003, 1.85km^2) and Dargall Lane at Loch Dee (80005, 2.07km^2). The BFIHOST distribution is, as expected, skewed towards lower BFI values due to the greater extent of less permeable soils and geologies within Scotland. Similarly, higher SAAR values and PROPWET values are also found within the dataset. A consequence of the higher PROPWET values is that it is a less important discriminatory variable than within England and Wales. A higher proportion of steep catchments are also found within the dataset. DPLBAR, which is correlated with area, indicates a similar distribution except for the two outliers which are the two larger catchments.

It can be concluded that the new calibration dataset provides a marked improvement in representing the climatic and hydrogeological variability across Scotland, when compared with the original ReFH 101 catchment dataset which included only four Scottish catchments.

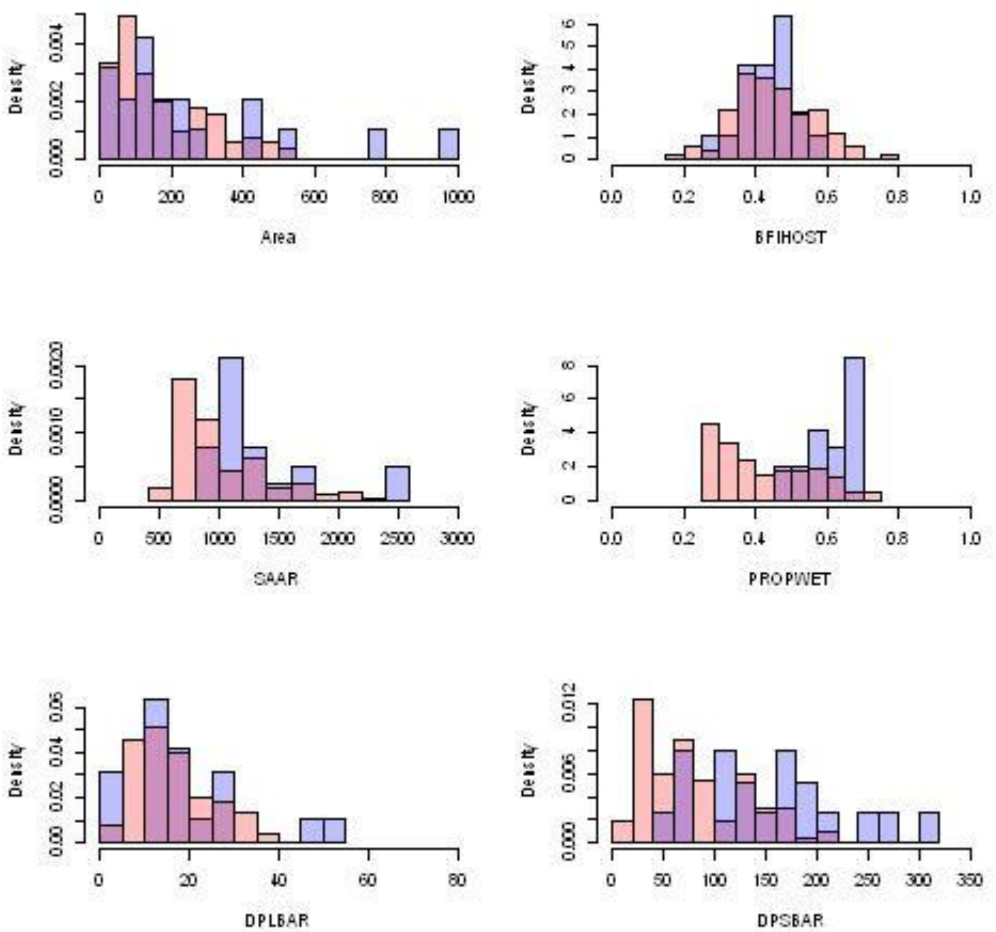

Figure 3. The distribution of the dominant catchment descriptors within the Scottish calibration data compared with the original calibration dataset. The Scottish dataset is coloured blue whilst the data for the original dataset is coloured red.

Figure 4 illustrates the location of the final Scottish calibration dataset together with the number of calibration events for each station.

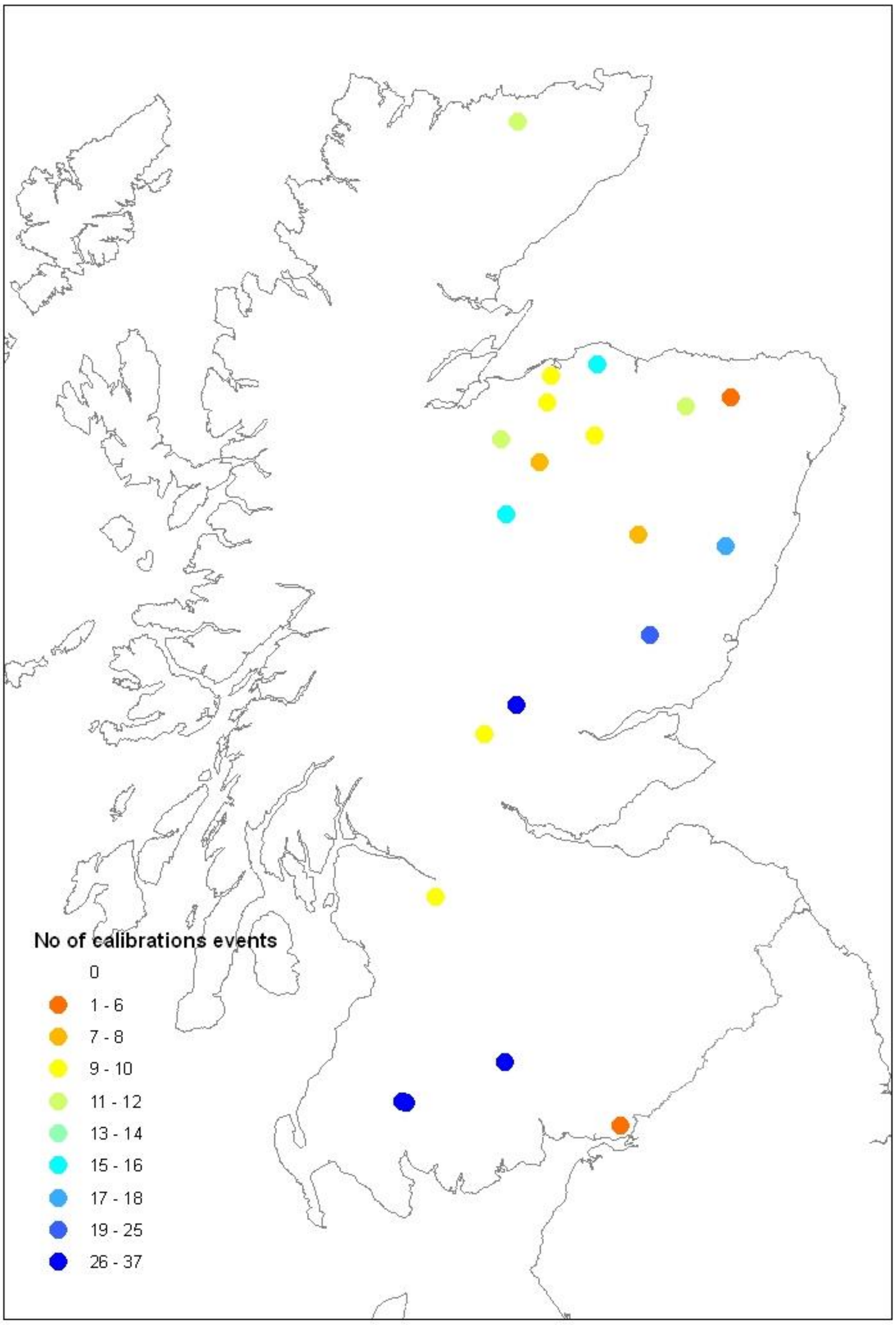

Figure 4. Location of calibration dataset with the number of events for which rainfall and flow data is available.

2.2 Quality control of the hydrometric data

A thorough and methodological approach to the quality control of input climatic data and calibration flow data (collectively termed model forcing data) is central to a well-founded modelling study. A summary of the data quality control is outlined below.

As discussed, two rainfall datasets were used within the calibration process:

1. The CERF rainfall data. The daily mean catchment average rainfall data and evaporation data were used to model antecedent soil moisture conditions within the model.
2. Autographic rain gauge data for the events modelled. Using data from one or more gauges these data were scaled to the catchment using the ratio of the CERF average rainfall and the rain gauge rainfall for the common period of record as a scaling factor.

A closed catchment water balance is a key aspect of any catchment scale modelling study. Failure to adequately close a catchment water balance may be a consequence of errors in the forcing data and/or an error in the assumption of the effective contributing catchment area above a gauging station. The catchment average rainfall and evaporation, together with the predicted annual runoff from the CERF model were compared to the measured annual runoff as measured at a gauging station. Where necessary the rainfall data (both CERF and event rainfall data) were rescaled using the ratio of the gauged annual runoff to the CERF annual runoff for the coincident period of record.

The flow events to be modelled were selected and assessed for data quality using the following process:

1. Candidate events were selected by extracting events with peak flow greater than 0.5 of the QMED estimated from the annual maxima series for the catchment. For stations with record lengths of less than 10 years, the selection threshold was set to the lower of the QMED estimate based on the observed data or catchment descriptor estimate of QMED obtained using the FEH statistical method implemented within WINFAP3.
2. Visual checks of each event were conducted noting whether the rainfall and flow event produce a hydrologically coherent event.
3. A crude base flow separation was applied to flow event and the fraction of the rainfall depth that the runoff depth represents was calculated to test whether the rainfall depth during an event was broadly consistent with the total depth of runoff product. This is broadly analogous to the standard percentage runoff, thus if the percentage runoff calculated in this manner was within 30% of the SPRHOST value for the catchment the event was judged to be suitable for use within calibration.

In cases where more than 10 events were identified using this process for a catchment, 10 events were used for calibration with the remainder being reserved for verification.

3 Model Calibration

Calibration of the events utilised the ReFH1 calibration software and the recommended calibration procedure enhanced with additional objective functions to measure goodness of fit. For each catchment the calibration event dataset was used to estimate the best overall set of model parameters (BL, BR, Tp and C_{max}) for the catchment.

The calibration procedure is presented in full detail within Kjeldsen et al. (2005)[6]. In summary, BL and BR are derived for each event based on the recession limb of the event hydrograph. The final values for the catchment are taken as an average of the estimates derived in this way.

Tp and C_{max} are then calibrated sequentially. The procedure optimised the model based on the flood peak, the delay between the rainfall event starting and the peak flow (referred to as the time to peak), and the runoff volume. This is a departure from the objective function used previously which was based on the root mean square error of the simulation as calculated between the flow estimation points of the simulation and the observed event, with these points defined by the simulation time step.

A summary of the model performance for the calibration and verification datasets is presented within Table 2 for each catchment considered.

[6] 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

Table 2. Summary of the Calibration and Verification Datasets

NRFA ID	Catchment	Number of events		Calibration Average percentage difference in			Verification Average percentage difference in		
		Calibration	Verification	Time to Peak	Peak Flow	Volume	Time to Peak	Peak Flow	Volume
7001	Findhorn at Shenachie	12	11	-1.25	5.76	-5.62	2.27	4.75	0.58
7002	Findhorn at Forres	10	0	5.70	8.77	0.36			
7005	Divie at Dunphail	10	0	-0.90	-0.01	1.41			
8004	Avon at Delnashaugh	9	0	-7.38	1.35	0.41			
8009	Dulnain at Balnaan	8	0	1.88	0.12	-1.10			
8013	Feshie at Feshiebridge	16	0	1.38	-3.96	4.35			
9001	Deveron at Avochie	12	0	3.23	-3.27	-11.04			
9002	Deveron at Muirsk	7	0	4.29	0.59	-1.26			
12006	Gairn at Invergairn	7	0	0.71	-3.41	-6.60			
12008	Feugh at Heughhead	17	17	2.53	-3.03	1.16	2.65	-0.87	8.60
13004	Prosen Water at Prosen Bridge	23	22	2.33	-4.21	-1.10	1.63	3.51	-0.38
15015	Almond at Newton Bridge	31	31	1.39	4.78	-4.03	0.55	-3.19	-10.87
16003	Ruchill Water at Cultybraggan	10	6	0.70	12.93	-11.27	0.17	5.77	-18.91
77004	Kirtle Water at Mossknowe	5	0	0.00	15.74	-0.53			
79004	Scar Water at Capenoch	29	29	-0.52	2.48	-6.73	0.10	4.73	-4.54
80003	White Laggan Burn at Loch Dee	37	36	-0.61	2.48	1.09	-0.43	-5.04	-6.73
80005	Dargall Lane at Loch Dee	31	31	-0.87	-12.83	-11.65	-1.47	-10.32	-7.69
84030	White Cart Water at Overlee	10	7	1.50	16.09	-0.70	-0.86	13.27	-2.66
96001	Halladale at Halladale	11	0	-0.09	0.23	0.22			

4 Increasing the sample set of catchments for derivation of the Time to Peak Tp parameter for use within Scotland

4.1 The Requirement

This section describes the development of an alternative Tp equation derived in consultation and agreement with SEPA and implemented within ReFH2.2 and above.

The Tp is the time-to-peak of the "kinked" instantaneous unit hydrograph (IUH) used within the routing model. The equation for calculating Tp is based on three catchment descriptors and has the form of:

Equation 1

$$T_p = aPROPWET^{-b}DPLBAR^{c}DPSBAR^{-d}$$

PROPWET is a measure of catchment saturation, DPLBAR is mean drainage path length (strongly correlated to catchment area but also influenced by shape) and DPSBAR is the mean drainage path gradient. That is, Tp would be expected to take a smaller value in small, steep, wet catchments.

Following the releases of versions 2.0 and 2.1 of the ReFH2 software, SEPA identified that the Scotland Time to Peak (Tp) estimates were smaller (resulting in shorter recommended duration events) and particularly so in larger, drier catchments when compared those of ReFH1 and the FSR rainfall runoff model.

The rationale for using catchments from Scotland only in the development of the model parameter equations was that the characteristics of the catchments across Scotland compared with the wider UK (increased topographic variation, generally higher rainfall except along parts of the east coast and generally impermeable catchments) warranted this approach. However, with a calibration data set of 19 catchments compared with 101 catchments for the UK model the design package in Scotland is informed by a smaller catchment pool.

An Extended Scotland dataset was derived, which incorporated a larger set of catchments drawing additional catchments from the north of England. The patterns in the values of the Tp parameter identified through calibration and the relationships with catchment descriptors were evaluated for the following catchment data sets:

- The ReFH2 "Scotland only" catchment set (19) as described in the earlier section of this appendix.
- A new Tp equation derived for an "Extended Scotland" catchment set (comprising the 19 Scottish catchments and 34 catchments drawn from the original 101 catchments used to parameterise ReFH1 and ReFH2 in England, Wales and Northern Ireland "EW&NI"); and
- the "EW&NI" Tp equation within ReFH 2.2 and above.

4.2 Development of the "Extended Scotland" catchment dataset

The catchment descriptors from the Tp equation, together with a consideration of catchment geology (using BFIHOST) and geographic proximity were used to develop the Extended Scotland (ExtScot) dataset. The variations in these descriptors across the Scottish catchments on the NRFA Peak Flows database were used as a general measure of the variation of these descriptors across Scotland.

On the basis of these considerations, the Scottish calibration dataset was extended by including catchments from the original ReFH1 101 calibration catchment dataset located within Hydrometric Areas 21 – 27 and Hydrometric Areas 64 – 68. The extended Scotland dataset has a membership of 54 catchments. Table 3 present the minimum, maximum and median for each catchment descriptor for the different calibration datasets. For comparison these are also presented for the 'as rural' catchments within Scotland from the NRFA Peak Flows dataset used within the development of the calibration of the ReFH2-FEH13 C_{ini} model (99 catchments).

Table 3. The minimum, maximum and median for each catchment descriptor for the calibration datasets and Scottish as rural catchments within the Peak Flows dataset.

Dataset	PROPWET			DPLBAR			DPSBAR		
	Min	Max	Median	Min	Max	Median	Min	Max	Median
Scottish NRFA 'as rural'	*0.3*	*0.9*	*0.6*	*2.1*	*87.4*	*21.3*	*30.4*	*441.8*	*121.7*
EW&NI Calibration	0.3	0.7	0.4	2.3	38.5	14.5	11.5	210.4	73.3
Scotland Calibration	0.5	0.7	0.64	1.6	54.5	16.6	55.1	307.5	146.5
Extended Scottish dataset	**0.3**	**0.7**	**0.6**	**1.6**	**54.5**	**16.7**	**12**	**307.5**	**117.3**

The extended Scottish dataset (ExtScot) is more representative of the variation of catchment descriptors observed within the NFRA Peak Flows catchments within Scotland than the Scottish calibration dataset only. It should be noted that catchments with low values of PROPWET combined with low DPSBAR are generally located in the south and east of England.

4.3 The catchment descriptor dependency of Tp across the United Kingdom

The variation in the calibrated values of Tp (i.e. those catchments in which ReFH has been specifically calibrated) as a function of the catchment descriptors within the Tp equation is plotted within Figure 5 to Figure 7 below. The calibration values are colour coded according to which data pool they lie in, with the "all calibration" dataset comprising all results across the UK.

The large values of Tp are only observed in dry, lowland catchments of the type that are not observed within Scotland. These catchments cover a wide range of scales and in these catchments it is DPLBAR (catchment scale) that is the strong differentiating catchment descriptor. This is not observed within either the Extended or Scotland only catchment datasets. This explains the strong dependency of Tp on catchment scale that is observed in the ReFH1 Tp equation, the FSR Tp equation and the ReFH2 EW&NI equation. All of these equations were developed using datasets that include these dry, lowland catchments.

The potential advantage of the extended Scotland dataset is that it does extend the dataset to cover a wider range of DPSBAR values, and through a larger sample size it does reinforce the basic relationships between Tp and catchment descriptors that are observed within the Scotland only data set.

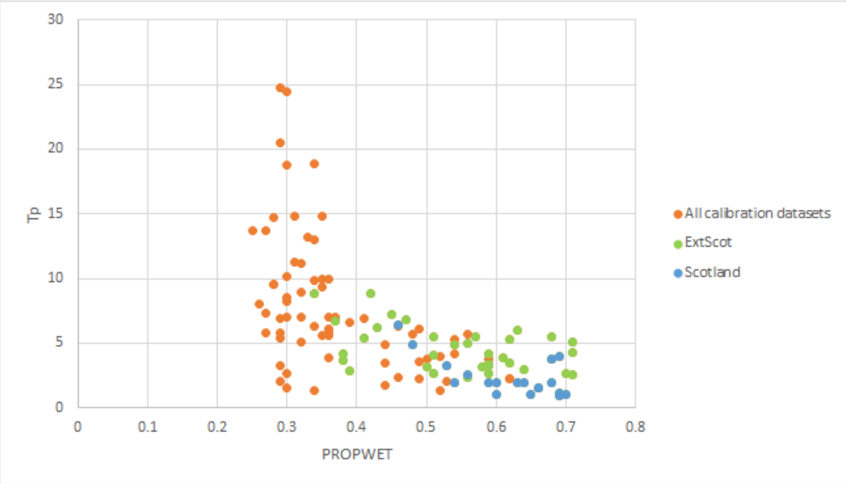

Figure 5 The Relationship between calibrated Tp values and PROPWET

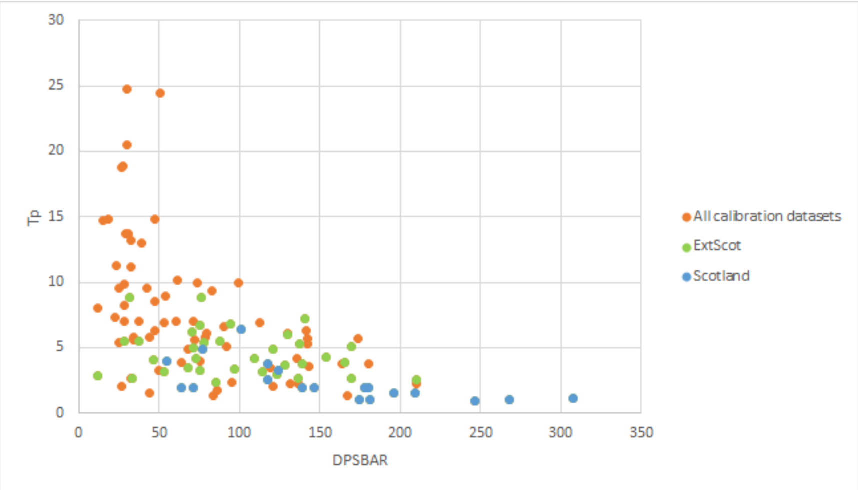

Figure 6 The Relationship between calibrated Tp values and DPSBAR

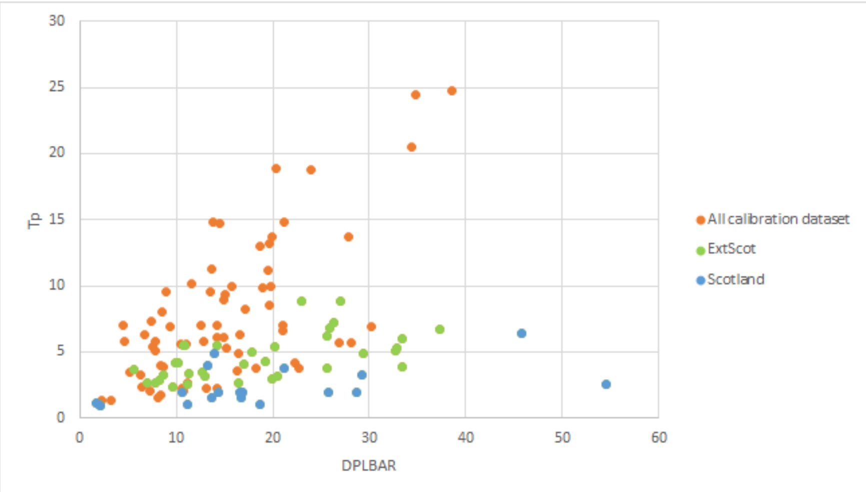

Figure 7 The Relationship between calibrated Tp values and DPLBAR

4.4 Derivation of a Tp equation using the ExtScot Dataset

The Tp model was re-parameterised using the ExtScot catchment dataset. The implication for the estimation of Tp values for catchments in the complete Scottish NRFA Peak Flows dataset is presented in Figure 8. The outlier station with a high Tp when using the Scotland Equation is gauging station 20002 which is a small (low DPLBAR) dry (low DPSBAR and PROPWET) catchment.

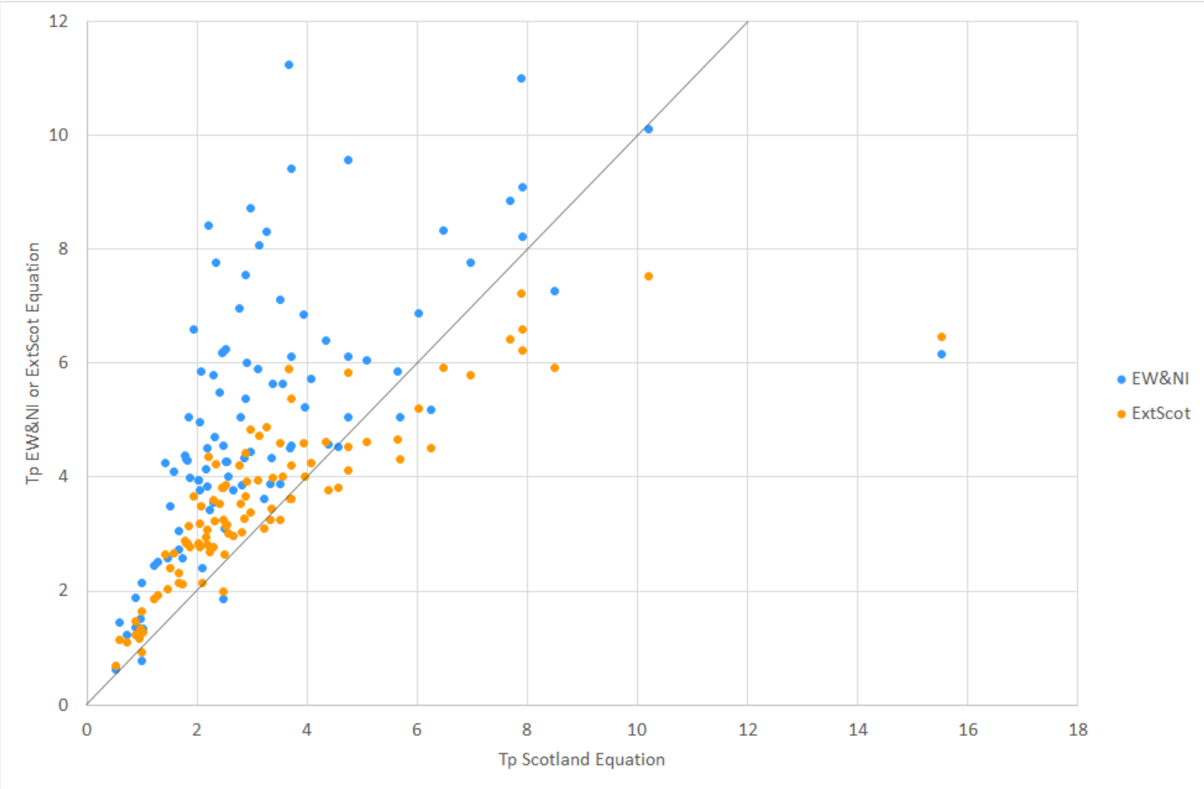

Figure 8. Tp values using the Scottish equation against Tp values using the EW&NI equation.

4.5 Comparison of Peak Flows

The peak flows generated within ReFH2-FEH13 using the two different equations have been compared with the peak flows derived using the enhanced statistical methodology across the NFRA Peak Flows catchments in Scotland.

The comparison has been undertaken for estimates of QMED, the 1 in 2 year return period and the 1 in 200 year return period. The statistical QMED is based on analysis of the at-site annual maxima series for each catchment and as it can be estimated with confidence from this series it can be considered as 'observed'. The Q(1:200) estimate is the at-site estimate generated using the FEH Enhanced Single Site estimation method and thus can be regarding as an alternative estimate of Q200 that makes maximum use of the at site data. The geometric bias at QMED and Q(1:200) between the at-site statistical estimates and the ReFH2-FEH13 estimates are presented in Table 4, together with bias corrected estimation of model FSE.

Table 4. The geometric bias and bias corrected FSE for QMED and Q(1:200) for the peak flow dataset between the enhanced statistical peak flow and the different ReFH2.2 models.

	QMED (99 catchments)	Q(1:200) (87 catchments)
Model Bias		
Scotland Tp	0.99	1.12
ScotExt Tp	0.87	0.97
Model FSE (bias corrected)		
Scotland Tp	1.33	1.46
ScotExt Tp	1.32	1.34

The results in Table 4 show that at QMED the new ScotExt Tp equation gives biased results for QMED (under-prediction on average) and fairly unbiased results at Q(1:200) (noting the statistical estimates at Q(1:200) are just alternative estimates). In contrast, the model is unbiased at QMED when the Scotland Tp model is used and tends to provide estimates that are on average 12% higher than the corresponding statistical estimates for Q(1:200).

The bias corrected FSE values are factorial standard errors calculated once the ReFH2 estimates have been corrected to remove any bias and are a measure of true unexplained variation. These results show that at QMED the unexplained variation is low for both cases and in both cases it is lower than that for the FEH QMED catchment descriptor equation without donor adjustment.

However, the FSE at Q(1:200) is much lower when the ScotExt Tp equation is used illustrating that there is a much better correlation between the FEH statistical estimates and the ReFH2 estimates across the NRFA Peak Flow catchments when the ScotExt Tp equation is used.

Based on this analysis the revised Tp equation has been incorporated within ReFH2.2 and above for use within Scotland.