ReFH2 Science Report

Evaluation of the Rural Design Event Model

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For and on behalf of Wallingford HydroSolutions Ltd.

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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.

The ReFH2 model has been extensively assessed by comparing the design package peak flow estimates generated from ReFH2 with both rainfall models and those generated using the statistical methods.

This Science Report presents the evaluation of the ReFH2 design model within UK 'as rural' catchments comparing the original (ReFH2.2) ReFH2-FEH13, ReFH2-FEH99 and FEH statistical method estimates. 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.

A comparison of the water balance ReFH2-FEH13 (ReFH2.3) and the original ReFH2-FEH13 (ReFH2.2) is presented in the 'ReFH2 Science Report: Closing a Water Balance' (2019)[4].

2 Comparison of ReFH2.2 with the FEH Enhanced Single Site and Pooled Statistical Methods

This comparison was made between ReFH2.2 and the FEH Enhanced Single Site and Pooled Statistical Methods across different 'as rural' datasets drawn from the NRFA Peak Flows dataset version 3.3.4 (the latest version at the time of assessment). The following criteria were applied to identify suitable catchments:

- FARL greater than 0.9 (identifying catchments free from the influence of large water bodies).
- URBEXT2000 is less than 0.03 (identifying catchments which are essentially rural).
- Classified as being either suitable for the estimation of QMED or Pooling.
- Length of record is greater than or equal to 14 years (suitable for the estimation of QMED).

The catchments were further subdivided by:

- Location: Scotland, England, or Wales.
- Permeability (England and one catchment in Wales): BFIHOST> 0.65 (permeable) and BFIHOST <0.65 (impermeable).

[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.

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

The ReFH2 model was applied in each catchment for the 1:2 (QMED), 1:100, 1:200 and 1:1000 return periods using the relevant country and catchment scale parameter estimation equations. The model was applied using both the FEH13 and legacy FEH99 rainfall models. The C_{ini} and BF_0 models used in the ReFH2 model are dependent upon the rainfall model used and Alpha was invoked for the FEH99 rainfall model results.

The ReFH estimates were evaluated through reference to the Enhanced Single Site FEH statistical methods estimates for each catchment. For the QMED flow, this is estimated directly from the gauged Annual Maximum series (AMAX) for the site. The Enhanced Single Site estimates were adopted for the long return period flows as the best estimate as the analysis gives greatest weight to the at site AMAX series. At short return periods these might be regarded as "observed", whilst at longer return periods these estimates are statistical method estimates, where the estimate is derived as the product of a pooled growth curve estimate with additional weight given to the at site data within the pooled growth curve combined with a local "observed" estimate of QMED.

The differences between the ReFH based estimates and the corresponding statistical estimates across the catchment datasets are summarised as a geometric mean (Bias) (expressed as a mean percentage difference) and corresponding Factorial Standard Error (FSE) for impermeable catchments within Table 1 and for permeable catchments within Table 2.

The primary methods of evaluation have been to compare the ReFH based estimates with estimates generated using the Enhanced Single Site analysis.

A comparison is also presented of the differences between "ungauged" pooled statistical estimates for the gauged catchments and the Enhanced Single Site estimates. These pooled estimates were derived using an estimate of QMED from the catchment descriptor equation and by excluding the at-site data from the pooling group. That is, the pooled estimates were derived treating the catchment as ungauged. The purpose of this comparison was to compare the ReFH2 model performance with that which might be expected from the statistical methods within an ungauged catchments prior to the incorporation of local data (such as donor adjustment of the Q_{MED} estimates). It is important to note that in this comparison local data are not used to adjust either the ReFH or Pooled estimates. Obviously, both are influenced by local data and both can be improved through the use of local data within a catchment specific application.

The key observations that can be drawn from the results presented in the tables are discussed by country below. However, **the overarching conclusion is that there is no requirement for the use of an Alpha parameter with the FEH13 rainfall model**.

2.1 England

Within the impermeable catchments:

- ReFH2-FEH13 is unbiased without the need for an alpha correction out to 1:200 but is biased with respect to the enhanced single site estimate by 12% at 1:1000.
- ReFH2-FEH99 with alpha invoked and the Pooled estimates are very similar in terms of bias.
- The pooled estimates have a low level of bias at all return periods with a tendency to underestimate slightly. This is likely to be associated with the CD based estimate of the index flood.
- The FSE values are lowest for ReFH2-FEH13 and the pooled estimates.

Within the permeable catchments:

- The bias observed with ReFH2-FEH13 is comparable to the bias observed in the pooled estimates to the 1:100 year return period and thereafter increases.
- The FSE for the pooled estimated and ReFH2-FEH13 are comparable.
- The statistical methods are generally perceived to under-estimate in permeable catchments this outcome is not inconsistent with this perception.

2.2 Wales

The patterns are generally consistent with those observed in England, but with the following differences:

- The bias in pooled estimates is low but consistently tends to overestimate.
- The bias in ReFH2-FEH13 shows a slight dependency with return period but is still generally low up to 1:200 and lower at 1:1000 than in England.
- The FSE for ReFH2-FEH13 and the pooled estimates are comparable with ReFH2-FEH99 alpha invoked having the lowest FSE values.

The general increase in bias observed at 1:1000 with ReFH2-FEH13 should be put into the context of current practice as recommended in the latest Environment Agency's Flood Estimation Handbook Guidelines (2012). Common practice for estimating the Q(1:1000) flow in England and Wales is based on scaling the Q(1:100) estimate derived via the statistical method by the ratio of the (1:1000) to (1:100) flow estimates derived using ReFH1. For REFH1 the geometric bias across England and Wales at the 1000 return period is approximately 16% with a strong bias in permeable catchments skewing this bias. In impermeable catchments it is in the order of 13%; i.e. very comparable to that observed with ReFH2 when used with FEH13.

This outcome with ReFH1 is entirely coincidental as the revision of Alpha for the original development of ReFH2 using the FEH99 model shows that rather than tending to a constant value beyond 1:150 (the calibrated limit of alpha for REFH1), Alpha rapidly decreases with increasing return period and thus with hindsight the ReFH1 values of Alpha should not have been extrapolated to 1:1000.

2.3 Scotland

The patterns in Scotland for the ungauged site application of the pooled statistical method are quite different with the pooled estimates and hence ReFH2-FEH99 Alpha invoked being very biased towards under estimation at longer return periods. The bias in the pooled estimates is reduced significantly when donor catchments are introduced to constrain the estimation of QMED. The ReFH2-FEH13 model is unbiased at QMED but generally presents a bias towards higher estimates than the corresponding enhanced single site estimates at higher return periods.

Table 1. A comparison of ReFH2 (ReFH2.2) model-based estimates and estimates produced by the Enhanced Single Site and pooled FEH statistical method for Impermeable Catchments.

		Bias %			*Factorial Standard Error (FSE)*		
		ReFH2		***Pooled***	***ReFH2***		***Pooled***
RP	***N***	***FEH13***	***FEH99***	***Statistical***	***FEH13***	***FEH99***	***Statistical***
England							
1:2	267	1	5	-4	1.43	1.50	1.40
1:30	172	-3	-3	-4	1.44	1.47	1.42
1:100	172	0	-4	-4	1.47	1.51	1.43
1:200	172	4	-5	-4	1.49	1.54	1.44
1:1000	172	12	-6	-4	1.56	1.63	1.46
Wales							
1:2	54	-3	-6	0	1.39	1.36	1.38
1:30	26	3	-1	5	1.41	1.33	1.40
1:100	26	5	-3	5	1.45	1.34	1.41
1:200	26	6	-5	5	1.47	1.35	1.42
1:1000	26	8	-7	5	1.49	1.38	1.43
Scotland							
1:2	99	-1	2	-16	1.33	1.33	1.38
1:30	87	7	-5	-17	1.44	1.39	1.41
1:100	87	10	-11	-16	1.46	1.42	1.42
1:200	87	12	-15	-16	1.48	1.46	1.43
1:1000	87	15	-26	-16	1.54	1.59	1.44

Table 2. A comparison of ReFH2 (ReFH2.2) model-based estimates and estimates produced by the Enhanced Single Site and pooled FEH statistical method for Permeable Catchments.

		Bias %			*Factorial Standard Error (FSE)*		
		ReFH2		***Pooled***	***ReFH2***		***Pooled***
RP	***N***	***FEH13***	***FEH99***	***Statistical***	***FEH13***	***FEH99***	***Statistical***
1:2	73	-2	-14	-2	1.52	1.76	1.51
1:30	43	-1	-13	2	1.52	1.63	1.50
1:100	43	7	-5	3	1.56	1.59	1.50
1:200	43	14	1	4	1.60	1.59	1.50
1:1000	43	31	19	5	1.72	1.67	1.51

3 A comparison of ReFH2-FEH13, ReFH2-FEH99 and ReFH1

A comparison of the predictive performance of ReFH1 and the two ReFH2.2 design packages are summarised in terms of Bias and FSE within Table 3 and presented graphically within Figure 1. In this context Bias and FSE can be regarded as prediction error, as the observed QMED is estimated directly from the observed AMAX series for each catchment with a low sampling error.

Figure 1 illustrates that ReFH1 is significantly biased within catchments with observed QMED estimates of less than 10m^{3}s^{-1} and degree of bias increases as QMED decreases. These catchments are the smaller and lower specific discharge catchments within the dataset.

For impermeable catchment the mean bias for ReFH1, is 7% whilst the ReFH2.2 design estimates are is unbiased. The FSE values are very comparable. Within permeable catchments the bias within the REFH2-FEH13 is low whereas ReFH1 is very biased and ReFH2-FEH99 lies between the two. The ReFH2.2 larger FSE values for permeable catchments reflect the hydrological complexity of these catchments and this greater prediction uncertainty in permeable catchments is also seen in the residuals.

Table 3 A statistical comparison of ReFH1 and ReFH2 QMED estimates with observed QMED estimates.

		ReFH1	ReFH2-FEH99	ReFH2-FEH13
Impermeable (BFIHOST < 0.65)	BIAS	7%	0%	-1%
	FSE	1.47	1.45	1.40
Permeable (BFIHOST ≥ 0.65)	BIAS	-45%	-13%	-1%
	FSE	2.78	1.77	1.53

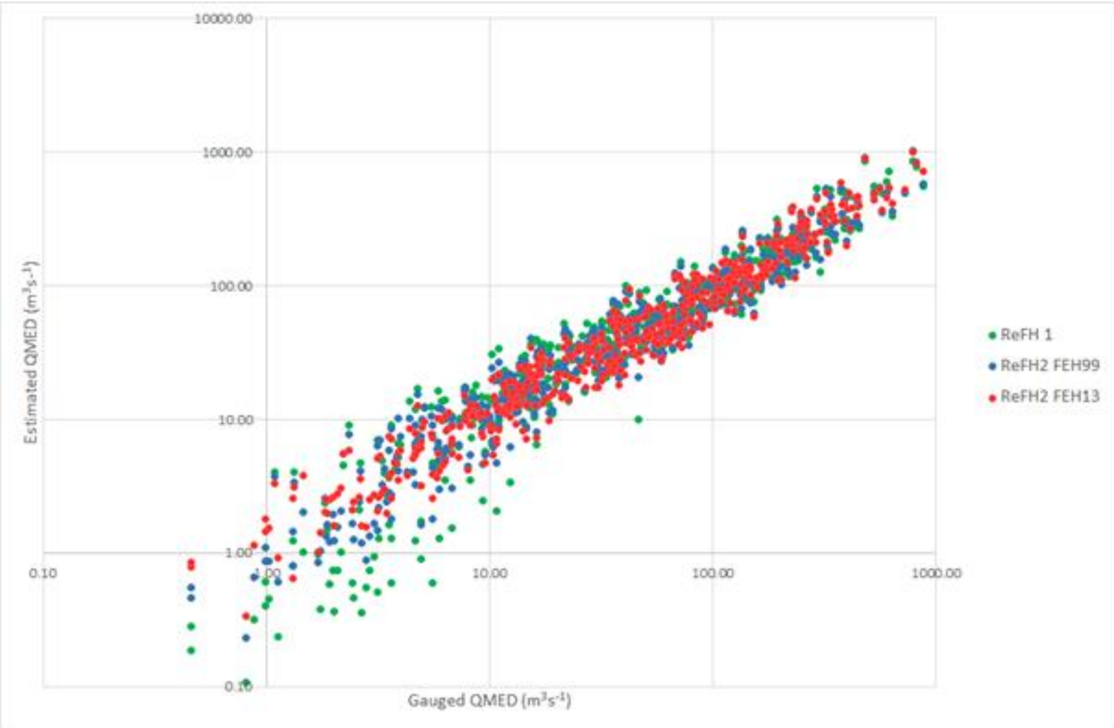

Figure 1 A comparison of observed, ReFH1, ReFH2-FEH99 and ReFH2-FEH13 QMED estimates

4 Summary

The ReFH2.2 model, when used in conjunction with rainfall estimates from the FEH13 rainfall model, is generally unbiased when compared with the enhanced single site estimates derived using the FEH statistical methods. The factorial standard error of estimate across the NRFA Peak Flows catchment dataset used for the assessment are also very comparable to those observed for the FEH pooled statistical method when the catchment is treated as ungauged. As there is no requirement for an alpha parameter when ReFH2 is used with the FEH13 rainfall, these ReFH2 estimates are completely independent of the statistical methods in application.

It is therefore concluded that for application within ungauged catchments **the ReFH2-FEH13 estimates and the pooled statistical estimates are comparable independent methods providing alternative estimates of peak flow within an ungauged catchment**. Having two independent FEH methods for estimating flood risk is a significant advance and reflects the value of the FEH13 rainfall model.

It should be noted that ReFH1 (both software and spreadsheet versions) is not calibrated for use with the FEH13 rainfall model and should not be used with the FEH13 rainfall model. Similarly, the FEH13 rainfall model should not be used with the FSR or FEH Restated FSR model for return periods out to 1:1000 years. The estimation of model performance at longer return periods has not been considered for this technical guidance and will be subject to future research.

Finally, the performance of ReFH2-FEH13 and ReFH2-FEH99 has been extensively evaluated across small catchments as part of the Environment Agency small catchment project[5]. This evaluation is presented in that recent research and confirms that the performance of ReFH2 methods in smaller (sub 40km^2) rural catchments is very comparable to the model performance across all rural catchments as presented in this report.

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