ReFH2 Science Report

The ReFH2-FEH99 initial conditions and the alpha parameter

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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 ReFH2 Technical Guide[3] presents the most up-to-date implementation of the methods 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[4]. This Science Report details the legacy ReFH2-FEH99 design package using the original FEH99 DDF model[5] (extracted from the ReFH2.2 Technical Guidance[6] published in 2016 as supporting documentation for ReFH2.3).

2 The ReFH1 Alpha Factor (α) and C_{ini}: A Historical perspective

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 catchment 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.

The original ReFH1 research was underpinned by the original FEH99 DDF rainfall model. Within that research, the design C_{ini} value was set to the (1:5) AEP peak flow estimated using the 1999 FEH Statistical Method as a reference using the ReFH1 set of 101 catchments. The ReFH1 model was run for each catchment with the design parameter estimates and the FEH (1:5) AEP design rainfall hyetograph. The C_{ini} value was then calculated as the initial soil moisture content required to ensure the ReFH1 peak flow estimate matched the 1:5 AEP peak flow estimate derived by the statistical method. An equation for estimating the ratio of C_{ini} to C_{max} from catchment descriptors was derived for the 101 catchments thus enabling the design C_{ini} to be estimated for the ungauged site. This baseline design estimate of C_{ini} was used for all AEPs within the ReFH1 model.

It was shown that when the ReFH1 model was applied to higher AEP rainfall events (for example the 1:100 AEP event) using the FEH99 DDF model, it yielded peak flows that were higher than the corresponding estimates derived using the statistical methods. The Alpha (α) factor was introduced to correct this effect. The α factor was calibrated to ensure that the peak flow estimated by ReFH1

[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] ReFH Technical Guide https://refhdocs.hydrosolutions.co.uk
[4] 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.
[5] Faulkner, D.S. 1999 Rainfall Frequency Estimation. Volume 2 of the Flood Estimation Handbook, Centre for Ecology and Hydrology
[6] Wallingford Hydrosolutions 2016. The Revitalised Flood Hydrograph Model ReFH2.2 Technical Guidance.

had the same AEP as the corresponding design rainfall event. The α factor was calibrated for events up to the 1:150 AEP event which led to the recommendation that ReFH1 should not be used for events that were more extreme than this.

In the ReFH1 model application, the influence of α is to reduce C_{ini} for more extreme events, which is counter intuitive as it is reasonable that if there is a trend in antecedent soil moisture conditions, that trend would be toward higher initial soil moisture conditions for the more extreme events. This conceptual issue, together with the lack of independence between the two FEH methods once α was applied in ungauged catchments, was largely responsible for the ReFH1 model not being adopted for use in Scotland.

2.1 REFH2-FEH99 Alpha (α) invoked: Estimation of α and the 1:5 AEP C_{ini}

The format of the original ReFH equation allows the 1:5 AEP C_{ini} values to take negative values in dry, highly permeable catchments. Whilst catchments of this type are predominantly on the chalk and limestone outcrops of southern England, the revised ReFH2-FEH99 structure of the equation ensures that positive values of the 1:5 AEP C_{ini} are obtained in all catchments. By assuming α is equal to 1.0 for a 1:5 AEP event, the corresponding values of C_{ini} were derived by calibrating C_{ini} such that the peak flow estimates from ReFH equalled the derived 1:5 AEP estimates with the FEH Statistical Method estimate of the 1:5 AEP peak flow. This analysis was undertaken for the ReFH1 data set of 101 catchments across the UK.

The revised form of the equation to estimate the 1:5 AEP C_{ini} improved the peak flow estimation in permeable catchments, when compared to the Statistical Method, particularly at lower AEPs. Two equations for the 1:5 AEP C_{ini} parameter were developed, which are applied to impermeable and permeable catchments depending on the catchment BFIHOST value;

Equation 1

$$\frac{C_{ini}}{C_{max}} = a \times Exp\big(b \times (BFIHOST - c)\big) \qquad for\ BFIHOST < 0.65$$

Equation 2

$$\frac{C_{ini}}{C_{max}} = a \times Exp(b \times BFIHOST) \qquad for\ BFIHOST \geq 0.65$$

Although the original ReFH1 model included both BFIHOST and PROPWET as explanatory variables, the revision identified that only the BFIHOST parameter was statistically significant once the distinction between equations for permeable and impermeable catchments was made.

It should be noted that the revised C_{ini} equations ensured that the C_{ini} value does not fall below zero. The model was developed using the 101 catchments from the ReFH1 calibration dataset which contains more catchments from England and Wales than Scotland.

Faulkner and Barber[7] reported that the ReFH1 model, when used with the FEH99 DDF model had a tendency to over-estimate peak flow, as compared to the FEH statistical method, in catchments with high SAAR values.

The model for estimating α when ReFH2 is used with the FEH99 DDF model was revised. The Statistical Methods, as deployed in WINFAP3 with the AMAX data updated to 2011, were used to generate peak flow estimates using the Enhanced Single Site approach. Events up to a 1:1000 AEP were simulated. The results were analysed and models developed to estimate α for a range of typical AEPs. The final model included Standard Average Annual Rainfall (SAAR) as an explanatory variable. The form of this model is presented within Equation 3:

Equation 3

$$LN(\alpha_{T,i}) = \rho_0 + \rho_1 . LN(SAAR_i) \qquad for\ SAAR_i > 500mm$$

$$\alpha_{T,i} = 1.0 \qquad for\ SAAR_i \leq 500m$$

where p_0 and p_1 are the model parameters defined for each AEP expressed as a return period of (T) years and SAAR is the standard average annual rainfall or 1961-1990 for the *i*th selected value of SAAR.

The break point of 500mm is defined by the lowest SAAR value in the data set. Numerical optimisation was used to estimate the two model parameters (p_0 and p_1) by minimising the squared difference between observed and predicted α value.

The variation of the estimated α value with SAAR for a range of typical AEPs is illustrated on Figure 1. The ReFH1 model would have predicted a constant α value for each AEP. For example, the estimate of α for the 1:100 AEP event would plot as a horizontal line at a value of α = 0.833. Interpolation is applied to estimate an α value between the AEPs shown.

[7] Faulkner, D. S. and Barber, S, 2009, Performance of the revitalised flood hydrograph method. Journal of Flood Risk Management, 2(4), 254-261. DOI: 10.1111/j.1753-318X.2009.01042.x

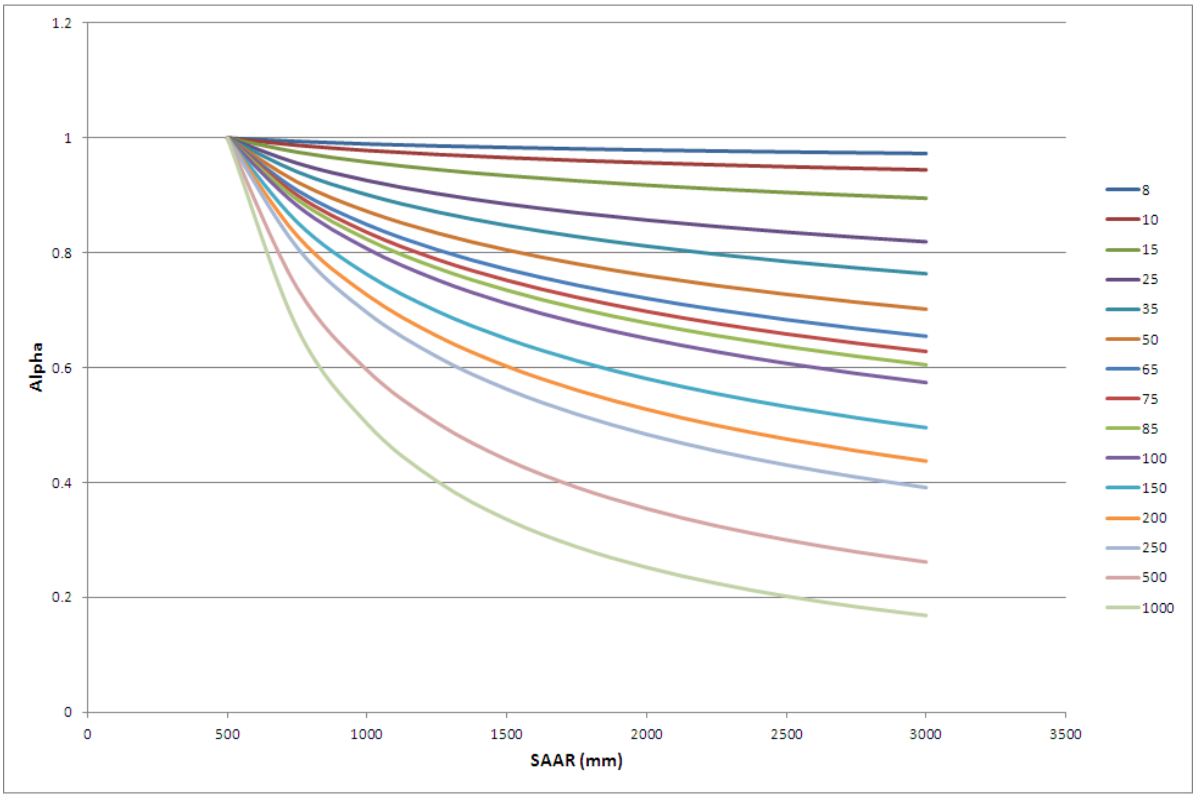

Figure 1. Alpha values plotted against SAAR for a range of Annual Exceedance Probabilities.

2.2 ReFH2-FEH99 Alpha not invoked: Estimation of the 1:2 AEP (QMED) C_{ini} and BF_0

When α is not invoked and the FEH99 model is used, ReFH2 uses a lower 1:2 AEP value of C_{ini} and a revised set of equations for estimating BF_0 as the C_{ini} is an explanatory variable for estimating the initial baseflow. The use of these revised initial conditions significantly reduces the need to constrain C_{ini} values for higher AEP events through the use of Alpha in less permeable catchments. This approach was developed for application in Scotland, but was also evaluated across all catchments within the NRFA peak flows data set classified as suitable for pooling and/or QMED estimation.

The estimation of an appropriate value of C_{ini} is a critical step in the design package. Evaluating the design package for ReFH2 in Scotland identified that the 1:5 AEP C_{ini} values were significantly higher than the range of C_{ini} values identified through calibration within the catchment dataset used to develop the design package within Scotland. Inspection of the seasonality and AEP of the events in the catchment datasets also identified that there was no significant relationship between the C_{ini} and the magnitude of the event and no strong seasonal dependency.

Without Alpha invoked, it was also identified that the estimates of longer return period peak flows were significantly higher than those estimated using the enhanced single site statistical methods. For these reasons a new C_{ini} model was developed based on the estimation of the 1:2 AEP C_{ini}.

The approach adopted considered all catchments from the NRFA peak flow dataset (formerly HiFlows UK) classified as suitable for the estimation of QMED. The process was follows, for each catchment:

- The 1:2 AEP design storm was estimated using the FEH99 DDF model in conjunction with the recommended duration.
- The ReFH model was run with design package parameter estimate and the design package estimate of the BF_0 initial condition.
- The value of C_{ini} required to calibrate the ReFH estimate of the 1:2 AEP peak flow to the value of QMED estimated directly from the gauged record was identified.
- The resultant set of C_{ini} values across all catchments was used to develop a model for estimating C_{ini} from catchment descriptors.

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. As the model parameters equations are also based on calibration results for observed events this approach to calibrating the 1:2 AEP C_{ini} model can be regarded as akin to a calibration against observed data. A subset of the NRFA Peak Flow Dataset 3.3.4 was used for the analysis. The dataset had 546 stations, consisting of catchments flagged as;

- Appropriate for the calculation of QMED;
- With more than 14 years of data (recommended for the calculation of QMED[8]);
- Rural (URBEXT2000<0.03); and
- As the impact of flood attenuation is not included within the generalised method of ReFH gauging stations with FARL<0.9 were also removed from the dataset.

The C_{ini} which provided the closest estimate to the QMED as estimated using the AMAX series was identified for the application of ReFH2 at each gauging station using the appropriate design parameter equations. Furthermore, in these catchments it was also generally observed that the QMED estimated using the statistical method QMED equation also under-estimated the observed QMED from the AMAX data. Thus, if the optimal C_{ini} value exceeded this value the catchment was excluded from the analysis. The optimised values were used to generate 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 normalised C_{ini} and BFIHOST provided the best fit for the data. The form of this relationship is:

Equation 4

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

As C_{ini} is an explanatory variable for the estimation of initial base flows, revised summer and winter models were required for use with the 1:2 AEP C_{ini} estimate. The form of the BF_0 equations were retained within this revision. As the focus of the research was in Scotland, these revised base flow equations were developed using the Scotland calibration catchments. However, the use of these equations has been extensively evaluated across the full NRFA Peak Flow catchment dataset and found to be suitable for catchments with BFIHOST values of less than 0.65 across the UK.

[8] Robson A & Reed D, 1999. Statistical procedures for flood frequency estimation, Flood Estimation Handbook Volume 3.