The Revitalised Flood Hydrograph Model
ReFH 2.2: Technical Guidance
Executive Summary

The Revitalised Rainfall-runoff model Version 2.2 (ReFH 2) model enables users to generate flood peaks flows and hydrographs from given rainfall events for both catchments and development sites.

Design flood events within the model are estimated using the corresponding design rainfall hyetographs. These hyetographs can either be derived from the new FEH13 Depth Duration Frequency (DDF) rainfall model or from the legacy FEH99 DDF model.

There are two sets of catchment model equations for estimating catchment parameters; one for England, Wales and Northern Ireland and one for Scotland; these are used in conjunction with initial conditions that are specified on the basis of country and rainfall model in use.

ReFH 2 is a recommended method within the 2015 CIRIA SuDS Manual (C753) for estimating greenfield runoff rates and volumes. The model includes parameter equation to facilitate application at the development site rather than catchment scale.

ReFH 2 models the influence of urbanisation on catchment flood regimes using an explicit model for the representing the impacts of urbanisation. With the ability to partitioning the catchment into greenfield and impervious surface components ReFH 2 is also recommended within the SuDS guidance for estimating brownfield runoff rates and volumes and runoff rates and volumes for simple site post development runoff rates and volumes.

There is no requirement for the FEH99 alpha parameter adjustment procedure when ReFH 2 is used with the FEH13 DDF model which means these estimates are entirely independent of the FEH statistical method estimates obtained using the WINFAP software. Comparisons with the statistical methods have demonstrated that the ReFH 2 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 within ungauged catchments is a significant advance and reflects the value of the new FEH13 rainfall model.

New for v2.2:

Enhancements within v.2.2 include:

- Options for using point or catchment exports from the FEH Web Service to support both catchment and development site (Greenfield and post development) applications.
- Enhanced support for estimating the impact of runoff from urban surface in small catchments and for plot scale applications as recommended by the 2015 CIRIA SuDS Manual.
- Support for modelling storm durations down to 5 minutes.
- Integration with the latest versions of XP Solutions’ MicroDrainage and Innovyse’s InfoWorks software.
- A revised Tp equation for Scotland, developed in consultation with SEPA and based using an expanded catchment dataset.
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1 Introduction

The purpose of this guidance document is to provide users of ReFH 2.2 with the necessary scientific background to the model. The document provides guidance on the use of the model ranging from the choice of rainfall model to the use of the model for both catchment and plot scale applications. Further information on use of the software is provided within the software help.

The ReFH 2 model is summarised within section 2. The differences between the FEH99 and FEH13 DDF rainfall models are discussed in the context of the application of ReFH 2 in section 3. The estimation of model parameters and initial conditions is described in sections 4 and 5. The predictive performance of ReFH 2.2 with both rainfall models is assessed within section 6.

The procedures for modelling the influence of urbanisation is described in detail within section 7 together with advice on using the software within urbanised catchments.

The guidance manual concludes with section 9. This final section describes how the ReFH software can be used to estimate greenfield runoff rates and volumes. The section also describes how the software can also be used to estimate brownfield runoff rates and volumes and runoff rates and volumes for simple post development sites. This advice follows the recommendations within the 2015 CIRIA SuDS Manual (793) that can be downloaded from the CIRIA website.
2 Summary of the ReFH 2 model

The Revitalised Rainfall-runoff (ReFH) model was first published in 2005\textsuperscript{1} as an update to the previous FEH rainfall-runoff method, the FSR/FEH rainfall-runoff method\textsuperscript{2}. The software implementation of the methods was accompanied by a comprehensive report describing the model development and application. The ReFH 1 methods for estimating design flood events were implemented within a spreadsheet (for design events) and extended to include model calibration functionality within the ReFH 1 flood modelling software\textsuperscript{3}. ReFH 2 has replaced the spreadsheet and the design package aspects of the ReFH 1 software.

The basic principles of the ReFH methods are presented here and a full description is provided by Kjeldsen et al\textsuperscript{1}. The ReFH 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 direct runoff. The rainfall losses are derived as the event unfolds, rather than being defined by a fixed value of percentage runoff. The routing component of ReFH uses the 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.

A schematic of the model is presented in Figure 1. The model is controlled by four model parameters and two model initial conditions which are presented in Table 1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{schematic.png}
\caption{Schematic representation of the ReFH model}
\end{figure}

\begin{itemize}
\item \textbf{Total rainfall}
\item \textbf{Net rainfall}
\item \textbf{Initial soil moisture} \( C_{\text{ini}} \)
\item \textbf{Initial baseflow} \( BF_0 \)
\item \textbf{Loss model} \( C_{\text{max}} \)
\item \textbf{Routing model} \( T_p \)
\item \textbf{Baseflow model} \( BR, BL \)
\item \textbf{Total flow}
\end{itemize}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\textbf{Parameter} & \textbf{Description} \\
\hline
\textbf{Loss model} & \( C_{\text{max}} \) \\
\textbf{Routing model} & \( T_p \) \\
\textbf{Baseflow model} & \( BR, BL \) \\
\hline
\end{tabular}
\caption{Model parameters and initial conditions}
\end{table}

\textsuperscript{3} ReFH software, 2007. WHS. \url{http://www.hydrosolutions.co.uk/products.asp?categoryID=4671}
Table 1. Summary of the six ReFH model parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter or Initial Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_p</td>
<td>Model Parameter</td>
<td>Unit hydrograph time to peak (hours)</td>
</tr>
<tr>
<td>B_L</td>
<td>Model Parameter</td>
<td>Baseflow recession constant or lag (hours)</td>
</tr>
<tr>
<td>B_R</td>
<td>Model Parameter</td>
<td>Baseflow recharge</td>
</tr>
<tr>
<td>C_Max</td>
<td>Model Parameter</td>
<td>Maximum soil moisture capacity (mm)</td>
</tr>
<tr>
<td>C_in_i</td>
<td>Initial Condition</td>
<td>Initial moisture content (mm)</td>
</tr>
<tr>
<td>B_F_0</td>
<td>Initial Condition</td>
<td>Initial baseflow (m³s⁻¹)</td>
</tr>
</tbody>
</table>

It is recommended that ReFH 2 is used in conjunction with the FEH13 DDF rainfall model⁴. The model can also still be used with the original FEH99 rainfall model.

When the model is used with the FEH99 rainfall model an additional parameter, the Alpha Factor (α), may be invoked. The purpose of α is to ensure that a FEH99 design rainfall event of a given return period translates to the same return period flow event by reducing runoff production as the return period increases. This parameter is not required when the FEH13 model is used as with this model the rainfall event of a given return period does generally translate to the same return period flow event without the need for this parameter. This outcome reflects the advance in the FEH13 rainfall model compared with the original FEH99 rainfall model.

The guidance within this document is focused on the ReFH 2 design package for use with the FEH99 and FEH13 DDF rainfall models. However, the ReFH model structure was developed such that it can be calibrated within a catchment using relatively small samples of event data. This is achieved using a calibration approach that enables the baseflow parameters to be directly estimated from event recession characteristics, thus increasing the identifiability of model parameters. The calibration of ReFH is not the subject of this guidance document and a ReFH calibration tool, with associated documentation, will be available in October 2016.

A consequence of this modelling approach is that ReFH 2 is not formally constrained to close a water balance. When the recommended event duration for a catchment is used this is not an issue. However, in small catchments and generally when events of durations well in excess of the recommended duration are used ReFH can sometimes violate a water balance. An algorithm has been incorporated into ReFH 2 to prevent this from occurring. This issue and the algorithm used to resolve it are discussed within Appendix 1.

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3 The choice of FEH rainfall model

ReFH 2 allows for the use of both the FEH99\(^5\) and FEH13\(^4\) Depth Duration and Frequency rainfall models. The depth for a given duration and frequency is assigned a storm profile based upon the season selected and is subject to both a seasonal correction factor and an area correction factor. This procedure is explained in full within Kjeldsen et al (2005)\(^1\).

ReFH 2 may be used with both FEH DDF models. However, the evaluation of ReFH methods demonstrates that ReFH 2 when used with the FEH13 model is an advance over both ReFH 1 and ReFH 2 when used with the FEH99 model. It is recommended that the FEH13 rainfall model should be used where these estimates are available. If these are not available it is recommended that ReFH 2 is used in conjunction with the FEH99 rainfall model. The FEH13 rainfall model should not be used with ReFH 1 or the restated FSR model. This is discussed in more detail within this section and a comparative evaluation of ReFH 2 using both models is presented within Section 6 together with a comparison of ReFH 2 and ReFH 1.

The original ReFH 1 research and ReFH 1 software were predicated on the FEH99 DDF model. As discussed, the original ReFH 1 research identified the requirement for the Alpha factor to ensure that when ReFH 1 was used with a design storm of a given frequency the simulated peak flow corresponded to the same frequency. The Alpha factor essentially modified the initial soil moisture condition to reduce initial soil moisture for more extreme rainfall events thus reducing the runoff volume and peak flow simulated by the model. A more detailed discussion of the background of \(\alpha\) is presented by Kjeldsen et al. Within ReFH 2 the value of Alpha used when the FEH99 model is invoked has been revised to address user experience\(^6\) that climate also influences the relationship between design rainfall AEP and predicted flow AEP. Within ReFH 2, when the FEH99 DDF model is selected, Alpha is dependent upon return period and annual rainfall. For a given return period the Alpha values are lower in areas of high rainfall.

The estimation of design initial conditions for both rainfall models and the estimation of Alpha for use when FEH99 is used are presented in detail within Appendix 3. The use of Alpha with the FEH99 DDF model is a pragmatic solution that is unattractive from a hydrological perspective. The required values of Alpha were identified by calibrating Alpha against the results from the statistical methods for selected catchments and developing a generalised model for estimating Alpha from return period and average annual rainfall. This introduces a second unattractive aspect; when the FEH99 rainfall model is used, and alpha is invoked, neither the ReFH 1 nor ReFH 2 methods can be regarded as being independent of the statistical method.

The use of FEH13 with an appropriate C\(_{ini}\) model dispenses with the requirement for an alpha parameter; that is the rainfall of a given AEP will yield a peak flow that is of comparable AEP. This is attractive from a hydrological perspective. Furthermore, this outcome also means that ReFH 2, when used with the FEH13 rainfall model, is independent of the statistical method. Thus when estimating the flood risk within an ungauged catchment the two approaches provide alternative, yet independent methods for estimation. This will lead to improved decision making within assessments.


This outcome is a consequence of the differences in the spatial patterns in rainfall depths between the two models and the dependency of these on return period. The FEH13 rainfall model is reported in detail by Stewart et al. The differences between the two rainfall models is illustrated in Figure 2. These results are the ratios of the FEH13 to the FEH99 rainfall depths for a 6 hour storm for the (1:100) and (1:200) return period.

There is a lot of detail within the spatial differences between the two models shown in these figures. However, the general patterns are that the FEH13 estimates tend to be lower (and by a greater amount) within areas of higher annual rainfall. In the drier areas of the UK the patterns are more mixed with greater rainfall depths observed in some areas, no change in others and lower depths in others. There is significant local detail in these patterns, for example some parts of the Scottish Highlands show significant increases in depths whereas the general pattern is one of general reductions in rainfall. Although not presented the spatial patterns do not show a significant dependency on event duration.

The ratios of depths for the NRFA Peak Flows catchments were extracted for the 1:2, 1:30, 1:100, 1:200 and 1:1000 AEP at the recommended durations for the catchments. The relationships between these ratios and annual average rainfall (SAAR) are presented separately within Figure 3 to Figure 5 for catchments in England, Scotland and Wales. The general patterns are that the FEH13 RMED values have a tendency to be lower in drier parts of the UK and higher in wetter parts of the country. As the AEP of the event increases this changes to a pattern where the FEH13 model depths are generally lower for drier parts of the country. At the 1:1000 AEP these ratios are generally lower for most catchments. The rate at which this pattern emerges, and the extent to which it emerges varies across the UK with this effect most marked within England and Wales.

These patterns illustrate why Alpha is not required when the FEH13 rainfall model is used. Generally for longer return periods and in wetter areas of the UK the FEH13 estimated rainfall depths are lower than the FEH99 rainfall depths. As discussed the Alpha parameter reduced the initial soil moisture depth in wetter parts of the UK and at longer return periods. This outcome would suggest that Alpha was needed to address a deficiency in the FEH 99 rainfall model.
Figure 2 Ratio of the FEH13 to FEH99 rainfall depths for the 1:100 and 1:200 6 hour storm
Figure 3  FEH13 to FEH99 DDF ratios for NFRA Peak Flow catchments in England

Figure 4  FEH13 to FEH99 DDF ratios for NFRA Peak Flow catchments in Scotland
Figure 5  FEH13 to FEH99 DDF ratios for NFRA Peak Flow catchments in Wales
4 Estimation of parameters for use within ungauged catchments

This section presents the derivation of equations relating the model parameters ($T_p$, $C_{\text{max}}$, $B_L$, and $B_R$) to catchment descriptors. These enable ReFH to be applied within a catchment without recourse to calibration. The key improvements within ReFH 2 relating to estimation of model parameters are:

- 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 1 research. A new set of parameter estimation equations were developed for Scotland. The development work was undertaken in partnership with SEPA using an extended set of calibration catchments within Scotland.

- The ReFH 2 methods include an explicit representation of the influence of urbanisation through a new urban runoff generation module (see Section 7). Thus an important distinction to make between the ReFH 2 and the ReFH 1 parameter equations is that the ReFH 2 equations are formulated to predict an "as rural" response to rainfall. In the formulation of these equations, for completeness, the URBEXT2000 catchment descriptor was used to describe the influence of the generally low levels of urbanisation within the calibrated catchment datasets. In application of the ReFH 2 model this descriptor is removed from the equations such that the model, when used with the equations, simulates an “as-rural” response. The urban runoff model incorporates how this “as rural” response is modified by the introduction of impervious surfaces and drainage within urban areas.

Latest research has shown that FEH methods are more accurate than methods such as IH124 for estimating peak flows within small catchments and for conducting plot scale greenfield runoff calculations. ReFH 2 is a recommended method within the 2015 CIRIA SuDS Manual for undertaking the estimation of greenfield runoff rates and volumes. It is also a recommended method for undertaking the estimation of post development runoff rates and volumes for simple developments. The inclusion of the catchment drainage network geometry descriptors DPLBAR (mean drainage path length) and DPSBAR (mean drainage path slope) in the equations for $T_p$ and $B_L$ in the ReFH 1 model limited the usefulness of the model for estimation of flows at the plot scale. Within the ReFH 2 model this has been addressed by developing “plot scale” models to estimate parameter values which use AREA as an alternative descriptor to DPLBAR and SAAR as an alternative to DPSBAR. Hence, ReFH 2 can be used directly to estimate greenfield runoff rates and volumes at the plot scale. The procedure for undertaking this analysis within the software is presented within Section 9.

The general form of the equations for estimating model parameters within the UK is shown in Table 2. The calibration of these equations is presented within Appendix 2.
<table>
<thead>
<tr>
<th>ReFH parameter</th>
<th>Application</th>
<th>Parameter estimation equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_p$</td>
<td>Catchment scale</td>
<td>$T_p = aPROPWET^bDPLBAR^c(1 + urbext2000)^dDPSBAR^e$</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>$T_p = aPROPWET^bAREA^c(1 + urbext2000)^dSAAR^e$</td>
</tr>
<tr>
<td>$C_{\text{Max}}$</td>
<td>Catchment and plot scale</td>
<td>$C_{\text{MAX}} = aPROPWET^b \exp(cBFIHOST)$</td>
</tr>
<tr>
<td>$B_L$</td>
<td>Catchment scale</td>
<td>$B_L = aPROPWET^bDPLBAR^c(1 + urbext2000)^dBFIHOST^e$</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>$B_L = aPROPWET^bAREA^c(1 + urbext2000)^dBFIHOST^e$</td>
</tr>
<tr>
<td>$B_R$</td>
<td>Catchment and plot scale</td>
<td>$B_R = aPROPWET^bBFIHOST^c$</td>
</tr>
</tbody>
</table>

The predictive performance of the equations for estimating $T_p$, $C_{\text{Max}}$, $B_L$, and $B_R$ are summarised in Table 3 and
Table 4 for catchment and plot scale applications.

**Table 3. Fit statistics for ReFH 2 parameter equations (England, Wales and Northern Ireland).**

<table>
<thead>
<tr>
<th>ReFH parameter</th>
<th>Application</th>
<th>R²</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>Catchment</td>
<td>0.80</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.71</td>
<td>1.36</td>
</tr>
<tr>
<td>CMax</td>
<td>Catchment and plot Scale</td>
<td>0.6</td>
<td>1.29</td>
</tr>
<tr>
<td>BL</td>
<td>Catchment</td>
<td>0.35</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.31</td>
<td>1.48</td>
</tr>
<tr>
<td>BR</td>
<td>Catchment and plot Scale</td>
<td>0.36</td>
<td>1.51</td>
</tr>
</tbody>
</table>
Table 4. Fit statistics for ReFH 2 parameter equations (Scotland).

<table>
<thead>
<tr>
<th>ReFH parameter</th>
<th>Application</th>
<th>R²</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_p$</td>
<td>Catchment</td>
<td>0.68</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.73</td>
<td>1.4</td>
</tr>
<tr>
<td>$C_{\text{Max}}$</td>
<td>Catchment and plot Scale</td>
<td>0.57</td>
<td>1.15</td>
</tr>
<tr>
<td>$B_L$</td>
<td>Catchment</td>
<td>0.72</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.73</td>
<td>1.2</td>
</tr>
<tr>
<td>$B_S$</td>
<td>Catchment and plot Scale</td>
<td>0.22</td>
<td>1.4</td>
</tr>
</tbody>
</table>

5 Initial conditions and the Alpha Factor ($\alpha$)

The $C_{\text{ini}}$ model parameter defines the initial conditions of soil moisture in the catchment at the start of a rainfall event. The value of $C_{\text{ini}}$ together with the value of initial Base Flow ($B_{F0}$) set the initial model conditions for ReFH. For a given catchment and rainfall event a lower $C_{\text{ini}}$ results in a hydrograph with a smaller peak flow.

The setting of these initial conditions for ReFH 2 and the dependency on rainfall model are presented in full within Appendix 3 and are summarised here.

5.1 ReFH 1 & ReFH 2: The FEH99 DDF model

The original ReFH 1 model was developed using the FEH99 DDF rainfall model. The original research developed equations to estimate a baseline value of $C_{\text{ini}}$ for ungauged catchments corresponding to the $C_{\text{ini}}$ for the 1:5 AEP event as defined by the FEH99 DDF rainfall model.

As discussed, the ReFH 1 model included another variable, Alpha ($\alpha$), which effectively adjusted the estimated $C_{\text{ini}}$ parameter so that, across the original calibration set of 101 catchments, the peak flows derived by the ReFH 1 model approximated the peak flows derived by the FEH Statistical Methods (as originally published in 1999). The relationship between $\alpha$ and AEP was calibrated for AEP values between 1:5 and 1:150. For AEP greater than 1:5 $\alpha$ has a value of less than one and for AEP less than 1:5 the value is set to 1. Within the model the $C_{\text{ini}}$ for longer AEPs was calculated as the product of $\alpha$ and the 1:5 AEP $C_{\text{ini}}$, that is the effective $C_{\text{ini}}$ decreases with increasing AEP.

The outcome that $C_{\text{ini}}$ decreases with increasing AEP is hydrologically counter-intuitive and this conceptual issue, together with the lack of independence between the two FEH methods once $\alpha$ was applied in ungauged catchments, was largely responsible for the ReFH 1 model not being adopted for use in Scotland by SEPA. Furthermore, in use it was identified that the value of $\alpha$ required also had a dependency on climate. The equation for estimating the 1:5 AEP $C_{\text{ini}}$ was also found to poorly define initial conditions within permeable catchments.
The development of Version 2.0 of ReFH 2 design package specifically addressed these issues. The estimation of $\alpha$ for use in conjunction with the 1:5 AEP $C_{ini}$ model was updated to include a dependency on average annual rainfall. Furthermore it was optimised against the Enhanced Single Site estimates of peak flow under the current generation of the FEH Statistical Methods for AEPs out to the 1:1000 AEP. The 1:5 AEP $C_{ini}$ model was also revised to improve the estimation of initial conditions in permeable catchments.

An alternative approach to setting initial conditions for the model was also developed based on revised models for setting $C_{ini}$ and $B_{F0}$ based on the 1:2 year (QMED) event and by reference to QMED estimates from observed data. The adoption of the lower value of $C_{ini}$ reduced the discrepancy between the peak flow estimated for a given return period using ReFH 2 and that estimated using the statistical methods.

Users are provided with the option of invoking $\alpha$ in the ReFH 2 design package when the FEH99 DDF model has been selected. Revised equations for estimating $\alpha$ and methods for applying $\alpha$ are also deployed within the software.

- If $\alpha$ is invoked then the new equations for estimating $\alpha$ are used. The revised set of equations for estimating the baseline 1:5 AEP $C_{ini}$ value are also used. The equations for estimating $B_{F0}$ are unchanged from the original ReFH 1 equations in this instance.

- If $\alpha$ is not invoked (the default condition for Scotland) then the alternative approach to estimating $C_{ini}$ based on estimating the $C_{ini}$ required to enable ReFH 2 to simulate the QMED accurately within a catchment. A revised set of $B_{F0}$ equations are used, with the 1:2 AEP $C_{ini}$ as an explanatory variable.

5.2 ReFH 2: The FEH13 DDF model

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 Section 6.1. The significant changes in the low AEP rainfall depths observed with the FEH13 rainfall model warranted a revision of the $C_{ini}$ model. A new FEH13 $C_{ini}(2)$ model has been developed for use when the FEH13 rainfall model is invoked. This has been calibrated using the same approach used to develop the FEH99 $C_{ini}(2)$ model for ReFH 2. In this approach the $C_{ini}$ value required for a catchment to estimate the $Q_{MED}$ event when ReFH 2 is used in conjunction with the design package model parameters and the $R_{MED}$ design storm for the recommended duration is identified. This is identified for all catchments within the NRFA peak flows database flagged as suitable for QMED estimation. A model relating these values to catchment descriptors is then identified.

Following this approach a single model was identified relating $C_{ini}(2)$ to BFIHOST for all catchments, irrespective of permeability. This is a hydrologically attractive outcome compared with the pragmatic necessity of defining two $C_{ini}$ models for use when ReFH 2 is used in conjunction with the FEH99 model.
6 Evaluation of the ReFH 2 design model across the UK

Benchmark example datasets of ReFH 2, ReFH 1 and FEH Enhanced Single Site statistical results are presented within Appendix 5. This appendix presents the results for the catchments used within the original calibration of the ReFH 1 model which have been included as part of the wider evaluation of the ReFH 2 model across the UK, described within this section.

6.1 Comparisons of ReFH 2 with the FEH Enhanced Single Site statistical methods and Pooled statistical methods

The ReFH 2 model has been extensively assessed by comparing the design package peak flow estimates generated from ReFH 2 with both rainfall models and those generated using the statistical methods across different, “as rural”, datasets drawn from the NRFA Peak Flows dataset version 3.3.4. The performance of the urban runoff model within ReFH 2 is discussed in 7.5. 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).

The ReFH 2 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 FEH99 and FEH13 rainfall models. For the FEH99 rainfall model ReFH 2 was applied with and without $\alpha$ invoked. As discussed previously, the $C_{\text{ini}}$ and $BF_0$ models used in the ReFH 2 model are dependent upon the rainfall model used and whether $\alpha$ is selected.

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 $Q_{\text{MED}}$.

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) within Table 5 for impermeable catchments and within Table 6 for permeable catchments.

The primary methods of evaluation has 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 ReFH 2 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 QMED 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, an overarching conclusion is that there is no requirement for the use of an Alpha parameter when the FEH13 rainfall model is used.

**England**

Within the impermeable catchments:

- ReFH 2 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.
- ReFH 2 FEH99 with alpha invoked and the Pooled estimates are very similar in terms of bias.
- ReFH 2 FEH99 without alpha invoked is unbiased at low return periods but with the bias rapidly increasing with return period and is very high at 1:1000.
- 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 ReFH 2 FEH13 and the pooled estimates.

Within the permeable catchments:

- The bias observed with ReFH 2 FEH 13 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 ReFH 2 FEH13 are comparable.
- The statistical methods are generally perceived to under-estimate in permeable catchments this outcome is not inconsistent with this perception.

**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 ReFH 2 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 ReFH FEH13 and the pooled estimates are comparable with ReFH FEH99 alpha invoked having the lowest FSE values.
The general increase in bias observed at 1:1000 with ReFH 2 FEH13 should be put into the context of current practice as recommended in the Environment Agency’s Flood Estimation Handbook Guidelines. Current practice for estimating the Q(1:1000) flow in England and Wales is commonly 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 ReFH 1. For ReFH 1 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 ReFH 2 when used with FEH13.

This outcome with ReFH 1 is entirely coincidental as the revision of Alpha for the original development of ReFH 2 shows that rather than tending to a constant value beyond 1:150 (the calibrated limit of alpha for ReFH 1) Alpha rapidly decreases with increasing return period and thus with hindsight the ReFH 1 values of Alpha should not have been extrapolated to 1:1000.

Scotland

The influence of the choice of rainfall model is demonstrated in the estimates without alpha invoked. The 2013 model yields lower bias estimates at 1:1000 estimates. At and below 1:200, the estimates using the 2013 model tent to be higher, although this is influenced by the outcome that the QMED estimates are biased towards under estimation.

The patterns in Scotland for the ungauged site application of the pooled statistical method are quite different with the pooled estimates and hence ReFH 2, 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.
Table 5. A comparison of ReFH 2 model-based estimates and estimates produced by the Enhanced Single Site and pooled FEH statistical method for Impermeable Catchments.

<table>
<thead>
<tr>
<th>Impermeable Catchments</th>
<th>Bias %</th>
<th>Pooled Statistical</th>
<th>Factorial Standard Error (FSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>ReFH 2</td>
</tr>
<tr>
<td><strong>England</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:2</td>
<td>267</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>1:30</td>
<td>172</td>
<td>-3</td>
<td>-1</td>
</tr>
<tr>
<td>1:100</td>
<td>172</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>1:200</td>
<td>172</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>1:1000</td>
<td>172</td>
<td>12</td>
<td>34</td>
</tr>
<tr>
<td><strong>Wales</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:2</td>
<td>54</td>
<td>-3</td>
<td>-11</td>
</tr>
<tr>
<td>1:30</td>
<td>26</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>1:100</td>
<td>26</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>1:200</td>
<td>26</td>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>1:1000</td>
<td>26</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td><strong>Scotland</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:2</td>
<td>99</td>
<td>-1</td>
<td>-5</td>
</tr>
<tr>
<td>1:30</td>
<td>87</td>
<td>7</td>
<td>-2</td>
</tr>
<tr>
<td>1:100</td>
<td>87</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>1:200</td>
<td>87</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>1:1000</td>
<td>87</td>
<td>15</td>
<td>25</td>
</tr>
</tbody>
</table>
Table 6. A comparison of ReFH 2 model-based estimates and estimates produced by the Enhanced Single Site and pooled FEH statistical method for Permeable Catchments.

<table>
<thead>
<tr>
<th>Permeable Catchments</th>
<th>Bias</th>
<th>Pooled Statistical</th>
<th>Bias</th>
<th>Pooled Statistical</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP</td>
<td>N</td>
<td>FEH13</td>
<td>FEH99 no Alpha</td>
<td>FEH99 Alpha</td>
</tr>
<tr>
<td>1:2</td>
<td>73</td>
<td>-2</td>
<td>N/A</td>
<td>-14</td>
</tr>
<tr>
<td>1:30</td>
<td>43</td>
<td>-1</td>
<td>N/A</td>
<td>-13</td>
</tr>
<tr>
<td>1:100</td>
<td>43</td>
<td>7</td>
<td>N/A</td>
<td>-5</td>
</tr>
<tr>
<td>1:200</td>
<td>43</td>
<td>14</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>1:1000</td>
<td>43</td>
<td>31</td>
<td>N/A</td>
<td>19</td>
</tr>
</tbody>
</table>
6.2 A comparison of ReFH 2 and ReFH 1

The predictive performance of ReFH 2 and ReFH 1 has been compared by comparing the QMED estimates obtained with the estimates of QMED derived from the observed data for all catchments classified as suitable for QMED estimation. The Scottish Environment Protection Agency has recommended that the alpha factor is not invoked when ReFH 2 is used within Scotland. In England and Wales the current guideline issued by the regulators is for alpha to be invoked. The comparison undertaken assumes that the alpha factor is set as recommended by the regulators. The alpha factor has also been invoked for catchments in Northern Ireland.

A comparison of the predictive performance of ReFH 1 and ReFH 2 at QMED is summarised in terms of BIAS and FSE within Table 7 and presented graphically within Figure 6. 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.

The figure illustrates that ReFH 1 is significantly biased within catchments with observed QMED estimates of less than 10m³s⁻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 ReFH 1 is 7% whilst ReFH 2 is unbiased. The FSE values are very comparable. Within permeable catchments the bias within ReFH 2 is low whereas ReFH 1 is very biased. The 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 7 A statistical comparison of ReFH 1 and ReFH 2 QMED estimates with observed QMED estimates.

<table>
<thead>
<tr>
<th></th>
<th>ReFH 1</th>
<th>ReFH 2 FEH99</th>
<th>ReFH 2 FEH13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impermeable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(BFIHOST &lt; 0.65)</td>
<td>BIAS</td>
<td>7%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>FSE</td>
<td>1.47</td>
<td>1.45</td>
</tr>
<tr>
<td>Permeable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(BFIHOST ≥ 0.65)</td>
<td>BIAS</td>
<td>-45%</td>
<td>-13%</td>
</tr>
<tr>
<td></td>
<td>FSE</td>
<td>2.78</td>
<td>1.77</td>
</tr>
</tbody>
</table>
6.3 Summary

ReFH 2 when used in conjunction with rainfall estimates from the new FEH13 rainfall model are 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 ReFH 2 is used with the FEH13 rainfall these ReFH 2 estimates are completely independent of the statistical methods in application.

It is therefore concluded that for application within ungauged catchments the ReFH 2 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 reflect the value of the new rainfall model.

It should be noted that ReFH 1 (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 FEH 13 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 of future research.
7 Impacts of urbanisation on flood hydrographs: the ReFH 2 urban runoff model

7.1 Model overview

It is generally accepted that an increase in urban extent and hence impervious area should result in decreased infiltration capacity and surface storage, thereby increasing runoff volumes. At the same time, the replacement of natural drainage paths with more efficient man-made drainage structures will reduce catchment response time. The combination of these two effects will both increase the peak flows experienced in urbanised catchments and the volume of direct runoff.

In the original development of the ReFH 1 methods the impact of urbanisation on the flood hydrograph was incorporated through the inclusion of URBEXT2000 within the catchment descriptor equations for estimating the parameters $T_p$ (unit hydrograph time to peak in hours) and $B_l$ (baseflow recession constant or lag in hours). Hence a catchment with a high proportion of urban extents would have a lower time to peak than a more rural catchment and a lower baseflow lag. It has been shown that this is a generic model and is not really suitable for use on catchment with extensive urban land cover, Kjeldsen et al. (2005) 7.

The redeveloped ReFH 2 method allows the urban component of the hydrograph to be modelled explicitly within the main model components: the loss model, routing model and baseflow model. The approach is described in more detail by Kjeldsen et al. (2013) 8 and summarised in the following sections.

7.2 Loss Model

The percentage runoff is considered as a weighted sum of the contributions from the rural and urban parts of the catchment. The percentage runoff is therefore estimated separately for each of the main two land cover classes urban (which include urban, suburban and inland bare ground) and rural (non-urban) as shown in Equation 1.

Equation 1

$$PR = (1-URBAN_{50k}) \cdot PR^{(rural)} + URBAN_{50k} \cdot PR^{(urban)}$$

where $PR^{(rural)}$ is the percentage runoff from the rural part of the catchment estimated using the original loss model and $PR^{(urban)}$ is the percentage runoff from the urban area. $URBAN_{50k}$ (as mapped on the Ordnance Survey 1:50K Land ranger map series).

Note that $URBAN_{50k}$ can be estimated from URBEXT2000 using Equation 2.

Equation 2

$$URBAN_{50k} = 1.567 \cdot URBEXT_{2000}$$

---

Based on values in current literature, Kjeldsen et al. (2013), suggest it is appropriate to define 30% of an urban area as impervious area and the Percentage Runoff for the urban area $PR^{(\text{urban})}$ consists of contribution from both impervious and pervious areas as shown in Equation 3.

**Equation 3**

$PR^{(\text{urban})} = 0.3 \cdot PR^{(\text{imp})} + 0.7 \cdot PR^{(\text{rural})}$

If it is assumed that this 30% impervious fraction of the catchment is fixed, then combining and simplifying these two equations yields Equation 4.

**Equation 4**

$PR^{(\text{urban})} = (1 - 0.4701 \times URBEXT_{2000}) \cdot PR^{(\text{rural})} + 0.4701 \times URBEXT_{2000} \cdot PR^{(\text{imp})}$

Allowing the fraction of impervious surface (IF) within the urban area yields a general form of Equation 4:

**Equation 5**

$PR = (1 - 1.567 \cdot IF \cdot URBEXT_{2000}) \cdot PR^{(\text{rural})} + 1.567 \cdot IF \cdot URBEXT_{2000} \cdot PR^{(\text{imp})}$

The maximum percentage runoff that can be generated from an impervious surface is 100% of the rainfall that is incident upon the surface. This assumes that all runoff from impervious surfaces is captured by surface water drains. In practice only a fraction of the rainfall will form runoff and commonly this is assumed to be in the region of 70%. If the fraction of rainfall that forms runoff from impervious surfaces is defined as the Impervious Runoff Factor (IRF) then:

**Equation 6**

$PR^{(\text{imp})} = IRF \cdot 100 \cdot R$

Where $R$ is the total rainfall depth over the event. Within ReFH 2 the IF and IRF values are user defined values (as these are properties of the type of urban area) for which defaults of 0.3 for IF and 0.7 IRF are proposed (see section 7.5). Within ReFH 2 Equation 5 is multiplied through by $R/100$ to convert the calculation to units of depth and applied to each time step within the event. The ReFH rural direct runoff is the basis of the calculation of rural runoff and the impervious runoff calculated from the product of IRF and the rainfall depth within the time step.

### 7.3 Routing Model

For catchment application the impact of urbanisation on the reduction in response time has been made by introducing separate unit hydrographs for routing the excess rainfall generated from the rural and urban (comprising both impervious and pervious parts of the catchments). The $T_p$, time to peak parameter value, for the urban area is expressed as a ratio of the (larger) $T_p$ for the rural area to the urban $T_p$. The same basic dimensionless shape of the Unit Hydrograph has been retained as for the rural area. For the seven catchments used by Kjeldsen et al. to verify the model against observed data the $T_p$ ratio varied from 0.19 to 0.55. However, it should be noted that these were relatively minor storm events.
7.4 Baseflow model

Within the ReFH 2 model there is a direct link between the routed direct runoff and recharge within the baseflow model, i.e. an increase in routed direct runoff from the urban area would result in an axiomatic increase in baseflow. This is hydrologically counter-intuitive hence the baseflow routing is modified such that the recharge is related to only the direct runoff from the rural area.

7.5 Suggested default values for the urbanisation model

Kjeldsen, et al.\textsuperscript{1} considered modelling results from small catchments that would be considered as heavily urbanised using observed but relatively small magnitude storm events. The paper identified $T_p$ multipliers in the region of 0.25 used in conjunction with values of IRF and IF fixed at values of 0.7 and 0.3 respectively. To define default values for the design package this analysis has been extended to consider the results obtained applying ReFH 2 to catchments classed as suitable for QMED estimation and that are classed as being heavily urbanised or greater ($\text{URBEXT2000} \geq 0.15$). ReFH 2 was applied using a winter storm. The "as rural" model residuals are presented within Figure 7. The data shows that the "as rural" estimates of QMED tend to underestimate the observed value with an increasing degree of urbanisation.

The ReFH 2 model was then reapplied using a range of $T_p$ ratios and values for the Impervious Fraction but retained a fixed value of 0.7 for the Impervious Runoff Factor (IRF). The Bias in the residuals and the Root Mean Square Error of the residuals were calculated for each combination of $T_p$ ratio and IF for catchments classified as being very, or extremely heavily urbanised ($\text{URBEXT2000} \geq 0.3$). The results are presented in Table 8 and Table 9 and show that minimum values were obtained for an IF value of 0.3 and a $T_p$ ratio of 0.5. These values are set as the defaults within the software.
Figure 7 The relationship between rural ReFH 2 model residuals for QMED within increasing levels of urbanisation

Table 8 BIAS of model residuals for catchments with URBEXT2000 values ≥ 0.3

<table>
<thead>
<tr>
<th>$T_p$ ratio</th>
<th>Impervious fraction (0 – 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td>0.5</td>
<td>0.09</td>
</tr>
<tr>
<td>0.75</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 9 RMSE of model residuals for catchments with URBEXT2000 values ≥ 0.3

<table>
<thead>
<tr>
<th>$T_p$ ratio</th>
<th>Impervious fraction (0 – 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>0.5</td>
<td>0.11</td>
</tr>
<tr>
<td>0.75</td>
<td>0.13</td>
</tr>
</tbody>
</table>
8 Using the urban runoff model within the ReFH 2 software

8.1 Modelling the impact of urbanisation at the catchment scale

The urban method described has been implemented within the ReFH 2 software with additional functionality to allow for the capture of runoff from the urban area by a sewer system that exports water from the catchment being modelled. This section describes the use of the ReFH 2 software for estimating the impact of urbanisation on flood hydrographs within a catchment scale application.

An example screen shot of the software user interface is shown in Figure 8 with the urbanisation tab selected.

![Figure 8 Screenshot from the model results window of the ReFH 2 software with the Urbanisation tab selected.](image)

Ongoing research on small urban catchments has shown that the seasonal signal that storms occur in urban catchments in summer is only discernible in very heavily urbanised catchments. The default values of IRF and IF for ReFH 2 were based on an analysis of residuals using winter storms. It is therefore recommended that the winter storm defaults should be used in all but the most heavily urbanised catchments. The data entry form on the tab opens with default values for all the parameters that the user can modify.
The definitions of each parameter are described below:

- **The Urban area** (km²) is the value representing the mapped urbanised area within the catchment. The default value is defined by using Equation 2 to estimate URBAN_{50k} which is then multiplied by the total catchment area (see Section 7.2). For very heavily urbanised catchments (URBEXT_{2000} >0.6) Equation 2 cannot be used as it will predict an URBAN_{50k} area larger than the actual catchment; once this limit is reached the software will constrain the urban area value. If your catchment is very heavily urbanised, you should manually set the urban area, imperviousness factor and urban runoff factors to reflect your catchment specific conditions as the model results will be very sensitive to these choices (see Section 7.2 for further detail).

- **The Urban Runoff Factor** represents the proportion of rainfall that results in direct runoff for the defined urban area. By default this is set to 0.7.

- **The Imperviousness Factor** defines the proportion of the identified urban area which is impervious, for example covered by roofs, paving or roads. By default this is set to 0.3 (i.e. 30% of the urban area is assumed to be impervious). You may need to adjust this value to suit the density of urban development in your urban area.

- **The T_p scaling factor** is the factor applied to the rural T_p (on the Model Parameters tab) to derive the time to peak to be used for routing the urban runoff through the unit hydrograph. The default value for the T_p scaling factor is 0.5.

- **Urban area served by sewers (UASS) (km²)** is the portion of the urban area over which the sewer systems collects and export water from the catchment. Therefore, this area must be less than or equal to the size of the urban area. The sewer functionality is only used if it is believed the sewers discharge outside of the catchment or below the point of interest.

- **The Sewer capacity** (m³/s⁻¹) is the maximum flow rate that the sewer system is assumed to be able to convey flows out of the catchment. These flows are effectively removed from the runoff hydrograph produced by the ReFH 2 model. Runoff from the proportion of the urban area served by sewers (UASS) will be removed from the catchment until the sewer capacity is reached. The remaining rainfall will then be subjected to the same losses and routing applied to the rainfall over the rest of the urban area. The capacity of the sewer system in an urban area can be estimated as the rainfall event which it is able to convey without significant overflows. Typically, older sewer systems are able to convey the 1 in 10 AEP rainfall event and newer systems the 1 in 30 AEP rainfall event.

It is common industry practice to use the 1:10 AEP event rainfall intensities to set these capacities. To simulate this in ReFH 2 you need to go back to the Rainfall Screen and select the 1:10 or 1:30 AEP rainfall event. You will see that the total rainfall depth is displayed above the hyetograph. Note this total rainfall (Rainfall_{TOTAL}) and the duration of the event. The capacity of the sewer in flow units can be estimated from the total 1:10 AEP rainfall depth as shown in Equation 7. Note that if you change the UASS you will need to recalculate your sewer capacity.

**Equation 7**

\[
\text{Sewer capacity (m}^3/\text{s)} = \frac{UASS \times \text{Rainfall}_{TOTAL}}{3.6 \times \text{Duration}}
\]

Where UASS (km²) is the defined urban area served by sewers, Rainfall_{TOTAL} (mm) is the total rainfall depth associated with the rainfall event setting the sewer capacity (for example, the 1:10 AEP rainfall event) and Duration (hours) is the duration of the rainfall event setting the sewer capacity. The calculated sewer capacity is in flow units (m³/s⁻¹).
9 Plot scale applications: greenfield, post-development and brownfield runoff rates and volumes

As discussed in this guidance document, latest research has shown that FEH methods are more accurate than methods such as IH124 for estimating peak flows within small catchments and for conducting plot scale greenfield runoff calculations. ReFH 2 is a recommended method within the current CIRIA SuDs manual for undertaking the estimation of greenfield runoff rates and volumes using the rural model. It is also a recommended method for undertaking the estimation of post development runoff rates and volumes for simple developments using the urban modelling capabilities.

This section describes the direct use of ReFH 2 for undertaking these analyses and should be read in conjunction with the SuDs manual.

ReFH v2.2 has been integrated within XP Solutions MicroDrainage drainage design software and if you have ReFH v2.2 installed on your PC you can access the software through MicroDrainage. For this category of use please refer to the MicroDrainage software documentation.

ReFH v2.2 can accept both catchment and point exports of design rainfall and catchment descriptors from the FEH Web Service. For assessing the runoff from development sites it is anticipated that the usual route would be to use a point export from the FEH Web Service for your development site.

The software automatically selects the plot scale equations for Time to Peak ($T_p$) and Baseflow Lag ($B_L$) at the point of import if you are using a point export within the software. If you are using a catchment export then you will need to select the use of the plot scale equations on the Catchment Details tab to apply the ReFH 2 model at plot scale. This is achieved via a tick box at the import of catchment descriptors and will result in the plot scale equations being utilised for the analysis (see Table 10).

9.1 Greenfield runoff rate and volume calculations

Greenfield sites are typically located on the periphery of existing developments and are sites with no urban development and hence can be assumed as being completely rural (fully pervious).

The parameters $T_p$ and $B_L$ depend on the size of the catchment and for larger catchments the geometry of the catchment. The plot scale equations for $T_p$ and $B_L$ are hence sensitive to the catchment area specified for use in the equations.

The SuDS guidance recommends that for plot scale areas of less than 0.5km$^2$ (50ha) in size, greenfield runoff calculations are estimated based on an area of 0.5km$^2$ and then rescaled to the actual size of the catchment. ReFH 2 can be used to implement this procedure using the following steps to calculate greenfield runoff rates and volumes.
9.1.1 Greenfield runoff rate calculation steps

The first steps are to identify the model parameters that are appropriate for an area of 0.5km$^2$ (50ha). The approach will differ slightly depending on whether you either use a catchment or point export file from the FEH Web Service. The first three steps are as follows:

1. Design equations: Select to use plot scale equations on the modelling screen if you are using a catchment import file. If you are a point data import file these are selected automatically.
2. Rainfall Parameters: On the rainfall screen accept the initial rainfall defaults as all return periods for drainage design are included by default. Set the Areal Reduction Factor (ARF) to 1.0 and accept the default seasonality of a winter storm.
3. Catchment area: On the modelling screen set the catchment area to the default development area of 0.5 km$^2$ (50ha) if your development area is less than 50ha and set it to your development area if greater than 50ha.

The software will then estimate the $T_p$ and $B_l$ parameters based on the 0.5km$^2$. You will need to record these parameters. The rainfall event duration is also dependent upon $T_p$ but the software will automatically set this for a given value of $T_p$. The final step, step 4, is to configure ReFH 2.2 for the actual extent of the site to enable both runoff rates and volumes to be estimated for the site.

4. Configure ReFH 2 for the actual extent of your development area: on the modelling screen reset the catchment area to the correct area of your development area and override the $T_p$ and $B_l$ parameters with the values you recorded when the catchment area was set to 0.5km$^2$.

Step 4 will also automatically set the recommended duration to that for the 0.5km$^2$ extent. This effectively rescales your results as recommended by the SuDs guidance on model parameters if your site is less than 50ha.

Having completed steps 1-4, the greenfield peak flow can either be read from the “as rural” results presented in the software or exported via the export button saves the summary statistics of peak flow and direct runoff volume for all modelled return periods to a CSV file. The default return periods encompass all the design return periods specified within the SuDs guidance. For a given AEP the peak flow is reported with units of m$^3$s$^{-1}$. The peak flow can be converted to a runoff rate with units of litres per second per hectare (L/s/ha) using Equation 8:

Equation 8

Greenfield runoff rate = \( \frac{10 \times \text{Peak flow}}{\text{Area}} \)

Where the runoff rates is in (L/s/ha), the peak flow is in (m$^3$s$^{-1}$) and the catchment area is in (km$^2$).
9.1.2 Greenfield runoff volume

The next step is to estimate the allowable greenfield runoff volume that can be discharged (at the greenfield flow rates) during an event. This runoff volume for a development site is usually defined as the 1:100 year 6 hour duration design event based on research by Kellagher (2002). The final step, step 5, in the ReFH 2 procedure to achieve this after estimating the runoff rates is as follows:

5. Reset the recommended duration: in the rainfall modelling screen override the duration for the 0.5km² parameter set by setting it to 6 hrs.

Having completed step 5, the greenfield volume, with units of mega litres, can be read from the "as rural" results presented in the software or exported using the Export button.

The hydrograph from which the volume is estimated can also be exported. This has units of m³s⁻¹. If you wish to convert this hydrograph to a volume within each time step it is necessary to multiply the ordinates of the hydrograph by the number of seconds in the model time step. The time step is specified in the rainfall modelling screen and the tubular results with units of hours:mm:ss and thus you will need to calculate the number of seconds in the model time step.

It is recommended that the project file is saved after step 4 and then under a different file name under step 5. The file name for the save at step 4 should specify that this file relates to greenfield runoff rate calculations and the file name for the save at step 5 should specify that the file relates to greenfield runoff volume calculations. This audit trail will ensure that you will always be able to recreate your results and you will also be able to pass generated report and project files across to third parties as part of quality assurance procedures.

9.2 Calculation of post development runoff rates and volumes

ReFH 2 provides a simple and quick to apply procedure for estimating post development runoff rates and volumes. These procedures are appropriate at the outline planning step for a wide range of development types and for simple developments the same approach can be used for detailed design.

The post development runoff case is modelled using the urbanised results which considers the development site to consist of pervious and impervious surfaces in line with SuDs guidance.

Firstly you need to set up the ReFH 2 model to simulate the greenfield runoff rates and volumes, as described in the previous sub-section.

You then need to set the urban area to be equal to the total area of impervious surface planned for the post development case. You will then need to set the Imperviousness factor to 1.0 and Impervious Runoff Factor (IRF) to 1.0. In this way, you will simulate the entire urban area as an impervious surface and simulate all of the rainfall over the urban area being converted to runoff.

With the IRF set to 1 then 100% of the rainfall incident upon the impervious surface will form runoff and if it is set to 0.8 then 80% of the rainfall will form runoff.

---

The post development peak flow can then be read from the ‘urbanised’ results section and converted to runoff rates (l/s/ha) as previously described. Alternatively the post development peak flows and volumes for all return periods can be exported using the Export Button.

The 1:100 year 6 hour runoff volume can also be read from the urbanised results once the duration has been specified as 6 hours, as before for the greenfield case.

9.3 Calculation of brownfield runoff rates and volumes

Drainage design can be very complicated and specialist modelling codes will commonly be used for the detailed drainage design for other than simple development cases. At the outline planning stage, and particularly when considering current brownfield runoff rates detailed drainage design will not be feasible.

Brownfield runoff rates for developments can be modelled in exactly the same way as for the post development case by setting the urban area to be equal to current brownfield impervious area and proceeding as for the post development case.

If you wish to include the influence of sewer or drain capacities on the brownfield runoff from current urban areas sites you can undertake this using the functionality in the software in conjunction with the guidance on use provided for the urbanised catchment case.

You might wish to consider this if part of the current, brownfield impervious surface is drained to sewer and potentially exported from the downstream catchment.

To achieve this you would set the area of the sewer system to the area of impervious surface that is positively drained. The sewer system will effectively remove runoff from the catchment up to the sewer capacity and is described in detail within Section 8.1. It is stressed that this functionality should only be used for outline design and should be confirmed using site specific information wherever possible.
Appendix 1  Closing a water balance within ReFH 2

1.1 Closing a water balance over an event

Defining a model to close a water balance over an event and confirming this closure against measurements is a significant challenge in hydrology. The initial conditions are a time dependent function of what has happened before the event whereas an event model such as ReFH defines this as a single value boundary condition. For example, the initial Base flow BF0 is a single value which is determined by ReFH to follow a first order decay, as determined by BL in the absence of further direct runoff. Whereas, in practice, whether baseflow is reducing prior to an event will be function of antecedent weather. The ability to uniquely measure and then model the catchment response to the entire depth of rainfall during an event would be confounded both by this and that in our temperate maritime climate it will have rained again before the total “baseflow” is measured.

To truly close a water balance over an individual event would point to a continuous simulation approach, rather than an event model. However, in practice it is very challenging to instrument a catchment to reliably capture all components of a water balance in even the simplest of catchments. A simple example of this is the density of rainfall measurements (ignoring hydrometric error) required to accurately estimate the spatial variation in rainfall across the catchment. Furthermore, continuous simulation requires the marshalling, quality assurance and management of very large volumes of data.

Even with a continuous simulation approach there is still the conundrum of the wide range of streamflow conditions that might result from an event of a given depth due to the duration and intensity profile of the event and the dependency on initial conditions. Thus in a design application there would still be the requirement to make simplifying decisions if anything other than a flood frequency relationship is going to be extracted from a continuous simulation model.

1.2 Why ReFH was not formulated to conserve mass?

ReFH estimates base flow for a time step from direct runoff in the time step, direct runoff in the previous time step and the base flow in the previous time step. This is a departure from common rainfall runoff model formulations in which effective rainfall is partitioned between baseflow and direct runoff based on catchment wetness (commonly represented by a soil moisture state variable). In ReFH, as simulated runoff is a function of catchment wetness, the baseflow is dependent upon catchment wetness. But the approach seems convoluted and, for the method to explicitly ensure that mass is conserved, the depth of water held in storage within the loss model would need to be reduced by an amount equivalent to the base flow in a time step. This does not take place within ReFH; the purpose of the loss model is to estimate direct runoff. If BR is less than 1 then ReFH does conserve mass as the loss model is uniformly distributed and C(t) does not exceed C_max in in practical application. If (1+BR)NetRainfall > TotalRainfall the model will violate conservation of mass by simulating more runoff than rainfall over the entire event.

In practice, in common with all models, ReFH can be calibrated to give a good model outcome over calibration events and this propagates into a generally good model performance over design events of the recommended duration. But once the application of the model is extrapolated to events of a duration that lies outside of the observed events the simulation performance of ReFH, and indeed any model will reduce. However, as ReFH is not constrained to ultimately conserve mass the outcome can, in some cases, be the unfeasible case of the model simulating more runoff than rainfall.
At first sight this appears to be a fundamental weakness of the model and perhaps an oversight in the development of the method. In practice ReFH was always designed to be calibrated against relatively sparse data sets. It has two initial conditions, a dynamic relationship between cumulative event rainfall and runoff generation within a time step and four model parameters.

It is very difficult to uniquely identify four parameters within a model against an objective function (measuring quality of fit), and very hard to do so over a small set of events. If the parameters are not orthogonal with regard to a calibration objective function the outcome is that you can obtain the same model outcome for a range of different combinations of model parameters; a lack of parameter identifiability.

In the conventional application of a model this is not an issue for calibration events but it can significantly reduce the ability of a model to accurately simulate events that lie outside the calibration range. Furthermore, if there are no observed data to evaluate how the model performs over these events (for example a design event) there is no direct information to judge how good the model simulation is in this case.

Parameter identifiability is also paramount for the development of relationships between model parameter sets calibrated over many catchments and catchment properties, as described by Catchment Descriptors. If parameters are not unique it is very difficult to develop these relationships and hence develop a design package. But if the number of parameters is reduced in search of identifiability there is commonly a potential reduction of model performance in calibration and generalisation.

In calibration ReFH addresses this dichotomy through the approach to calibration. The two baseflow parameters (the time constant BL and ratio of baseflow volume to direct runoff volume, BR) are estimated analytically from recession analysis of the events thus leaving two parameters ($C_{\text{max}}$ and $T_p$) to be estimated empirically against statistical objective functions. This sequential approach to optimisation seeks to ensure that the two parameters to be empirically calibrated are both orthogonal to one another.

This approach to maintaining a flexible modelling structure is at the expense of ensuring that the model conserves mass, irrespective of the overall quality of simulation. This trade-off is a good trade off so long as the model is not applied to events that are significantly longer that the critical/recommended duration of events. The duration of observed large events obviously tend towards to the critical duration event.

### 1.3 Ensuring Mass is conserved for durations in excess of the recommended duration.

The issue of water balance closure commonly appears when the ReFH model is being applied within small catchments with a duration set at that for the larger, downstream catchment. This is almost wholly an issue for when a hydraulic model is being calibrated across the catchment but can also occur when the critical duration for the inflow to a reservoir is being optimised.

To ensure that ReFH conserves mass in these situations the base flow model within ReFH 2 has been modified such that in the case $(BR+1)\text{NetRainfall} > \text{TotalRainfall}$ ReFH does not simulate more runoff than rainfall.
The modified base flow model is as follows. For time steps less than the sum of the Recommended Duration (Dr) and the time base (TB) of the “kinked” unit hydrograph (the duration of the direct runoff for an event of duration Dr) base flow is calculated as described by Kjeldsen et al1:

\[ Z_{t+\Delta t} = k_1q_t + K_2q_{t+\Delta t} + K_3Z_t, \]

and for time steps greater than for time steps greater than (Dr+TB) the baseflow will be calculated as:

\[ Z_{t+\Delta t} = (k_1q_t + k_2q_{t+\Delta t})(1-t/(D+TB))^{\beta} + k_3Z_t \]

Where D is the event duration. The nomenclature follows the standard ReFH nomenclature. Thus the base flow generation during an event of the recommended duration or less for a catchment is unaltered. Recognising that as the duration increased beyond the recommended duration the extrapolation of the model calibration of any model becomes more uncertain, the contribution of the direct runoff to the base flow will be increasingly reduced in accordance with the degree to which the recommended duration is exceeded.

The empirical parameter \( \beta \) is optimised within a model run to ensure that the sum of nett base flow and direct runoff over the duration of the event (defined by direct runoff) does not exceed total rainfall. Nett base flow is the base flow generated within the event and not the base flow contribution derived from the initial base flow (which will recess through the event).

This is a simple, transparent resolution of the issue that recognises, and resolves the practical issue of closing a water balance over event durations significantly in excess of the recommended duration. This solution does not introduce any change to the design package when used with the recommended duration and does not alter the simulation over the period recommended duration even when invoked for a long duration event.

Occasionally in very small catchments, and at long return periods the water balance is not closed at the recommended duration. In this instance the start of the water balance correction is brought forward to the first time step after the occurrence of the peak flow in the as-rural part of the catchment being simulated and \( \beta \) is optimised as for the extended duration case.
Appendix 2  Estimation of ReFH 2 model parameters for use within ungauged catchments

This appendix presents the derivation of relationships between the model parameters \( (T_P, C_{\text{Max}}, B_L, \) and \( B_R ) \) and catchment descriptors to enable ReFH 2 to be applied within a catchment without recourse to calibration. The key improvements within the ReFH 2 relating to estimation of model parameters are:

- 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 1 research. A new set of parameter estimation equations were developed for Scotland. The development work was undertaken in partnership with SEPA and used an extended set of calibration catchments within Scotland.

- "plot scale" models have been developed for ReFH 2 to estimate parameter values which use AREA as an alternative descriptor to DPLBAR and SAAR as an alternative to DPSBAR. Hence, ReFH 2 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 10. The calibration of these equations is discussed in the following sections of this document. The parameter equation for estimating \( T_P \) in Scotland has been revised for ReFH2.1 to reflect the operational experience of staff from the Scottish Environment Protection Agency. This revision is presented within Appendix 6.

### Table 10. Structure of equations estimating ReFH 2 model parameters

<table>
<thead>
<tr>
<th>ReFH parameter</th>
<th>Application</th>
<th>Parameter estimation equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_P )</td>
<td>Catchment scale</td>
<td>( T_P = a \text{PROPWET}^b \text{DPLBAR}^c (1 + \text{urbext2000})^d \text{DPSBAR}^e )</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>( T_P = a \text{PROPWET}^b \text{AREA}^c (1 + \text{urbext2000})^d \text{SAAR}^e )</td>
</tr>
<tr>
<td>( C_{\text{Max}} )</td>
<td>Catchment and plot scale</td>
<td>( C_{\text{MAX}} = a \text{PROPWET}^b \exp(c \text{BFIHOST}) )</td>
</tr>
<tr>
<td>( B_L )</td>
<td>Catchment scale</td>
<td>( B_L = a \text{PROPWET}^b \text{DPLBAR}^c (1 + \text{urbext2000})^d \text{BFIHOST}^e )</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>( B_L = a \text{PROPWET}^b \text{AREA}^c (1 + \text{urbext2000})^d \text{BFIHOST}^e )</td>
</tr>
<tr>
<td>( B_R )</td>
<td>Catchment and plot scale</td>
<td>( B_R = a \text{PROPWET}^b \text{BFIHOST}^c )</td>
</tr>
</tbody>
</table>

For all equations the parameter is estimated as a product of the catchment descriptors. The sensitivity 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 ReFH v2.1 parameter equations within Figure 9 and Figure 10. The catchment descriptors are described in detail within the Flood Estimation Handbook\textsuperscript{10}.

Considering the Time to Peak ($T_p$), 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 $T_p$ being particularly sensitive to PROPWET within drier catchments. In contrast the estimation of $T_p$ is very sensitive to the scale of the catchment (DPLBAR) in England, Wales and Northern Ireland and less so in Scotland. In Scotland $T_p$ 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.

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 $B_k$ 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 $B_k$ on PROPWET and BFIHOST are very similar. However, $C_{\text{max}}$ is more sensitive to PROPWET in Scotland and less sensitive to BFIHOST; again a reflection in the relatively variation in the descriptors across the UK.

Figure 9 Catchment descriptor dependencies for $T_p$ and $B_c$
Figure 10 Catchment descriptor dependencies for $B_R$ and $C_{\text{max}}$
2.1 Parameter estimation equations for use in Scotland

The selection and calibration of ReFH within catchments across Scotland is discussed in Appendix 4. This yields a set of 19 calibrated model parameter sets to form the basis of the parameter estimation equations for application in Scotland.

A key catchment descriptor within the original ReFH 1 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)\(^{11}\) often referred to as the BFIHOST. The BFIHOST is estimated using a regression model that explains the variability in BFI values across gauged catchments within Great Britain. This regression model was developed as a classification tool within the HOST project. 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\(^{12}\), 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.

Equations to estimate the four ReFH model parameters, \(T_p\), \(C_{Max}\), \(B_L\), and \(B_R\), 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 the \(C_{Max}\). 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 \(C_{Max}\), \(T_p\), BL, and BR are presented in Table 11 and illustrated in Figure 9 to Figure 12. These figures also illustrate the marginal benefit of using the Scotland specific BFIScot variable rather than BFIHOST. In summary, the new equations offer improved estimation of parameters in Scottish catchments. The plot scale equations for \(T_p\) and \(B_L\), perform similarly to the catchment scale equations and hence confirm that the ReFH 2 models are suitable for application at the plot scale.


\(^{12}\) www.sepa.org.uk/science_and_research/idoc.ashx?docid=afbf95859-0f25-4827-9210-411d2fae48ac&version=1
Table 11. Performance of equations for estimating ReFH model parameters in Scottish catchments.

<table>
<thead>
<tr>
<th>ReFH parameter</th>
<th>Application</th>
<th>R²</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>Catchment</td>
<td>0.68</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.73</td>
<td>1.4</td>
</tr>
<tr>
<td>CMax</td>
<td>Catchment and plot Scale</td>
<td>0.57</td>
<td>1.15</td>
</tr>
<tr>
<td>BL</td>
<td>Catchment</td>
<td>0.72</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.73</td>
<td>1.2</td>
</tr>
<tr>
<td>BR</td>
<td>Catchment and plot Scale</td>
<td>0.22</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Figure 11. Calibrated and estimated TP
Figure 12. Calibrated and estimated C_{max}

Figure 13. Calibrated and estimated B_{L}

Figure 14. Calibrated and estimated B_{R}
2.2 Parameter estimation equations for use in England, Wales and Northern Ireland

Equations to estimate the four main model parameters $T_p, C_{\text{Max}}, B_L$, and $B_R$ were developed using the searching algorithm described within the previous sub-section and a base data set of 101 catchments (the 101 catchments used to develop ReFH 1). Both catchment and plot scale formulations of the equations for $T_p$ and $B_L$ were developed.

The predictive performance of the equations for estimating $T_p, C_{\text{Max}}, B_L$, and $B_R$ is summarised in Table 12 for catchment and plot scale applications. Illustrations of model performance are shown on Figure 15 to Figure 18.

The new equations offer an improved estimation of parameters. The alternative equations for $T_p$ and $B_L$ indicate that there is little loss in performance thus allow the models to be used at the plot scale.


<table>
<thead>
<tr>
<th>ReFH parameter</th>
<th>Application</th>
<th>$R^2$</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_p$</td>
<td>Catchment</td>
<td>0.80</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.71</td>
<td>1.36</td>
</tr>
<tr>
<td>$C_{\text{Max}}$</td>
<td>Catchment and plot Scale</td>
<td>0.6</td>
<td>1.29</td>
</tr>
<tr>
<td>$B_L$</td>
<td>Catchment</td>
<td>0.35</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>Plot scale</td>
<td>0.31</td>
<td>1.48</td>
</tr>
<tr>
<td>$B_R$</td>
<td>Catchment and plot Scale</td>
<td>0.36</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Figure 15. Calibrated and estimated $T_p$
Figure 16. Calibrated and estimated $C_{\text{max}}$

Figure 17. Calibrated and estimated $B_L$

Figure 18. Calibrated and estimated $B_R$
Appendix 3 Revision of the FEH99 Alpha Factor ($\alpha$) and the model initial conditions

3.1 Initial conditions when using the FEH99 rainfall model

The ReFH 1 Alpha Factor ($\alpha$) and Cini: 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 peak flows and conversely if $C_{ini}$ is high, the hydrograph runoff volume and peak flow will be higher.

The original ReFH 1 research was underpinned by the original FEH99 Depth Duration Frequency (DDF) rainfall model. Within this research design $C_{ini}$ value was set to the (1:5) AEP peak flow estimated using the 1999 FEH Statistical Method and using the ReFH 1 set of 101 catchments. The ReFH 1 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 to be initial storage depth that was required to make the ReFH 1 peak flow estimate match the 1:5 AEP peak flow estimate derived by the Statistical Method. Then 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 ReFH 1 model.

It was shown that when the ReFH 1 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. Therefore, the ReFH 1 project steering committee decided to introduce $\alpha$ to correct this effect. The Alpha factor was calibrated to ensure that the peak flow estimated by ReFH 1 had the same AEP as the corresponding design rainfall event. The Alpha factor was calibrated for events up to the 1:150 AEP event which led to the recommendation that ReFH 1 should not be used for events that were more extreme than this.

In the ReFH 1 model application, the influence of $\alpha$ is to reduce $C_{ini}$ for more extreme events, which is counter intuitive as antecedent soil moisture conditions are likely to be wetter for the more extreme events. This conceptual issue, together with the lack of independence between the two FEH methods once $\alpha$ was applied in ungauged catchments, were largely responsible for the ReFH 1 model not being adopted for use in Scotland.

REFH 2 FEH99 DDF model, Alpha ($\alpha$) invoked: Estimation of $\alpha$ 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 structure of the format of the equation ensures that positive values of the 1:5 AEP $C_{ini}$ are obtained in all catchments. By assuming $\alpha$ 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 ReFH 1 data set of 101 catchments across the UK.
The revised form of the equation to estimate the 1:5 AEP $C_{ini}$ improves 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 9
\[
\frac{C_{ini}}{C_{max}} = a \times \exp\left( b \times (BFIHOST - c) \right) \quad \text{for } BFIHOST < 0.65
\]

Equation 10
\[
\frac{C_{ini}}{C_{max}} = a \times \exp\left( b \times BFIHOST \right) \quad \text{for } BFIHOST \geq 0.65
\]

Although the original ReFH 1 model included both BFIHOST and PROPWET as explanatory variables, the research underpinning ReFH 2 identified that only the BFIHOST parameter was statistically significant.

It should be noted that the revised $C_{ini}$ equation ensures that the $C_{ini}$ value does not fall below zero.

The model was developed using the 101 catchments from the ReFH 1 calibration dataset which contains more catchments from England and Wales than Scotland.

Faulkner and Barber\(^d\) reported that the ReFH 1 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 $\alpha$ when ReFH 2 is used with the FEH99 DDF model was revised. The current 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 $\alpha$ for a range of typical AEPs. The final model included Standard period Annual Rainfall (SAAR) as an explanatory variable. The form of this model is presented within Equation 10:

Equation 11
\[
LN(\alpha_{T,i}) = \rho_0 + \rho_1 . LN(SAAR_i) \quad \text{for } SAAR_i > 500\text{mm}
\]
\[
\alpha_{T,i} = 1.0 \quad \text{for } SAAR_i \leq 500\text{mm}
\]

where $\rho_0$ and $\rho_1$ 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 ($\rho_0$ and $\rho_1$) by minimising the squared difference between observed and predicted $\alpha$ value.

The variation of the estimated $\alpha$ value with SAAR for a range of typical AEPs is illustrated on Figure 19. The existing ReFH 1 model would predict a constant $\alpha$ value for each AEP. For example, the
estimate of $\alpha$ for the 1:100 AEP event would plot as a horizontal line at a value of $\alpha = 0.833$. Interpolation is applied to estimate an $\alpha$ value between the AEPs shown on this Figure.

Figure 19. Alpha values plotted against SAAR for a range of Annual Exceedance Probabilities.
FEH 99 DDF model, Alpha factor not invoked: estimation of the 1:2 AEP (QMED) C<sub>ini</sub> and BF<sub>0</sub>

When α is not invoked and the FEH99 model is used the software uses a lower, 1:2 AEP value of C<sub>ini</sub> and a revised set of equations for estimating BF<sub>0</sub> as the C<sub>ini</sub> is an explanatory variable for estimating the initial baseflow. The use of these revised initial conditions significantly reduces the need to constrain C<sub>ini</sub> values for higher AEP events through the use of Alpha in less permeable catchments. This approach was developed for application in Scotland but has also been 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<sub>ini</sub> is a critical step in the design package. Evaluating the design package for ReFH 2 in Scotland identified that the 1:5 AEP C<sub>ini</sub> values were significantly higher than the range of C<sub>ini</sub> 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<sub>ini</sub> and the magnitude of the event and no strong seasonal dependency.

Without Alpha invoked in ReFH 2 it was also identified that the estimates longer return period peak flows were significantly higher than those estimated using the enhanced single site statistical methods.

For these reasons a new C<sub>ini</sub> model was developed based on the estimation of the 1:2 AEP C<sub>ini</sub>. 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<sub>0</sub> initial condition.
- The value of C<sub>ini</sub> 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<sub>ini</sub> values across all catchments was used to develop a model for estimating C<sub>ini</sub> 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<sub>ini</sub> 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 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<sup>13</sup>)
- Rural (URBEXT2000<0.03).

---

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 dataset has 546 stations.

The Cini which provided the closest estimate to the QMED as estimated using the AMAX series was identified for the application of ReFH 2 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 Cini 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 Cini (defined as the ratio of Cini to Cmax). A linear relationship between the normalised Cini and BFIHOST provided the best fit for the data. The form of this relationship is:

Equation 12

\[
\frac{C_{ini}}{C_{max}} = a \cdot BFIHOST + b
\]

As Cini 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 Cini estimate. The form of the BF0 equations were retained within this revision. As the focus of this 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.

3.2 Initial Conditions when using the FEH13 DDF model

The significant changes in the low AEP rainfall depths observed with the FEH13 rainfall model warranted a revision of the Cini model. A new FEH13 Cini(2) model has been developed for use when the FEH13 rainfall model is invoked. This has been calibrated using the same approach used to develop the FEH99 Cini(2) model for ReFH 2. In this approach the Cini value required for a catchment to estimate the QMED event when ReFH 2 is used in conjunction with the design package model parameters and the RMED design storm for the recommended duration is identified. This is identified for all catchments within the NRFA peak flows database flagged as suitable for QMED estimation. A model relating these values to catchment descriptors is then identified.

Following this approach a single model was identified relating Cini(2) to BFIHOST for all catchments. That is, a single model can be fitted to all catchments irrespective of permeability. This is an intuitively attractive outcome compared with the pragmatic necessity of defining two Cini models for use when ReFH 2 is used in conjunction with the FEH99 model. The relationship between Cini(2)/Cmax and BFIHOST is presented in Figure 20 and is explained using a logarithmic regression model.
Figure 20 The relationship between the optimal $C_{\text{ini}(2)}$ and the BFIHOST value for stations from the NRFA Peak Flows dataset flagged as being suitable for $Q_{\text{MED}}$ estimation.
Appendix 4 Deriving catchment based parameter datasets for ReFH in Scotland

4.1 Collation and Summary of Scotland Dataset

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. 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\textsuperscript{14}) rainfall runoff model were used for this purpose. These data are available from 1961 to 2006 inclusive.

An initial dataset of 28 gauging stations was 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 13 and presented within Figure 21. If the FEH FARL (Flood Attenuation by Reservoir and Lakes) was less than 0.90 the station was excluded within the dataset as 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\textsuperscript{15}) 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 13. Gauging Stations considered for use within the ReFH calibration for Scotland.

<table>
<thead>
<tr>
<th>Accept or reason for rejection</th>
<th>NRFA ID</th>
<th>Catchment</th>
<th>AREA</th>
<th>No. Years of Rainfall and Flow Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>FARL</td>
<td>1001</td>
<td>Wick at Tarroul</td>
<td>158.18</td>
<td>9</td>
</tr>
<tr>
<td>FARL</td>
<td>2002</td>
<td>Brora at Bruachrobie</td>
<td>423.64</td>
<td>6</td>
</tr>
<tr>
<td>Data</td>
<td>3002</td>
<td>Carron at Sgodachail</td>
<td>236.58</td>
<td>0</td>
</tr>
<tr>
<td>Accept</td>
<td>7001</td>
<td>Findhorn at Shenachie</td>
<td>415.73</td>
<td>21</td>
</tr>
<tr>
<td>Accept</td>
<td>7002</td>
<td>Findhorn at Forres</td>
<td>781.69</td>
<td>21</td>
</tr>
<tr>
<td>Water Balance</td>
<td>7003</td>
<td>Lossie at Sheriffmills</td>
<td>216.66</td>
<td>8</td>
</tr>
<tr>
<td>Accept</td>
<td>7005</td>
<td>Divie at Dunphail</td>
<td>164.63</td>
<td>17</td>
</tr>
<tr>
<td>Accept</td>
<td>8004</td>
<td>Avon at Delnashaugh</td>
<td>540.58</td>
<td>11</td>
</tr>
<tr>
<td>Accept</td>
<td>8009</td>
<td>Dulpain at Balnaan</td>
<td>272.2</td>
<td>13</td>
</tr>
<tr>
<td>Accept</td>
<td>8013</td>
<td>Feshie at Feshiebridge</td>
<td>229.63</td>
<td>10</td>
</tr>
</tbody>
</table>


\textsuperscript{15} Personal Communication, Alistair Cargill, 2013, SEPA.
<table>
<thead>
<tr>
<th>Accept or reason for rejection</th>
<th>NRFA ID</th>
<th>Catchment</th>
<th>AREA</th>
<th>No. of Years of Rainfall and Flow Data</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Deveron at Avochie</td>
<td>444.84</td>
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</tr>
<tr>
<td>Accept</td>
<td>9002</td>
<td>Deveron at Muirsk</td>
<td>961.44</td>
<td>9</td>
</tr>
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<td>Data</td>
<td>9003</td>
<td>Isla at Grange</td>
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<tr>
<td>Accept</td>
<td>12006</td>
<td>Gairn at Invergairn</td>
<td>145.91</td>
<td>4</td>
</tr>
<tr>
<td>Accept</td>
<td>12008</td>
<td>Feugh at Heughhead</td>
<td>232.84</td>
<td>16</td>
</tr>
<tr>
<td>Accept</td>
<td>13004</td>
<td>Prosen Water at Prosen Bridge</td>
<td>107.6</td>
<td>14</td>
</tr>
<tr>
<td>Accept</td>
<td>15015</td>
<td>Almond at Newton Bridge</td>
<td>83.97</td>
<td>12</td>
</tr>
<tr>
<td>Accept</td>
<td>16003</td>
<td>Ruchill Water at Cultrybraggan</td>
<td>1.85</td>
<td>15</td>
</tr>
<tr>
<td>Accept</td>
<td>77004</td>
<td>Kirtle Water at Mosknewe</td>
<td>69.93</td>
<td>15</td>
</tr>
<tr>
<td>Accept</td>
<td>79004</td>
<td>Scar Water at Capenocho</td>
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<td>18</td>
</tr>
<tr>
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<td>White Laggan Burn at Loch Dee</td>
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<td>Dargall Lane at Loch Dee</td>
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<td>19</td>
</tr>
<tr>
<td>Accept</td>
<td>84030</td>
<td>White Cart Water at Overlee</td>
<td>106.42</td>
<td>15</td>
</tr>
<tr>
<td>Data</td>
<td>86001</td>
<td>Little Eachaig at Dalinlongart</td>
<td>31.85</td>
<td>0</td>
</tr>
<tr>
<td>FARL</td>
<td>92001</td>
<td>Shiel at Shielfoot</td>
<td>255.12</td>
<td>11</td>
</tr>
<tr>
<td>Accept</td>
<td>96001</td>
<td>Halladale at Halladale</td>
<td>193.72</td>
<td>11</td>
</tr>
<tr>
<td>FARL</td>
<td>96002</td>
<td>Naver at Apigill</td>
<td>474.05</td>
<td>16</td>
</tr>
<tr>
<td>FARL</td>
<td>96003</td>
<td>Strathy at Strathy Bridge</td>
<td>120.89</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 21 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 21. Location of Scottish gauging stations used within the ReFH calibration for Scotland.
Figure 22 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 22. 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 23 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 510km² used in the original calibration dataset; The Findhorn at Forres (7002) is 782km² and Deveron at Muirsk (9002) is 961km². There are also two catchments under 5km²; Ruchill Water at Culty Braggan (16003,
1.85km²) and Dargall Lane at Loch Dee (80005, 2.07km²). 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 dataset which included only four Scottish catchments.

Figure 23. 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 24 illustrates the location of the final Scottish calibration dataset together with the number of calibration events for each station.
Figure 24. Location of calibration dataset with the number of events for which rainfall and flow data is available.
4.2 Quality control of the 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.

**Rainfall Processing.**

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

- The CERF rainfall data. The daily mean catchment average rainfall data evaporation data were used to model antecedent soil moisture conditions within the model.

- Autographic rain gauge data for the events modelled. Using data from one or more gauges these data were scaled to the catchment scale 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.

**Quality control of event data.**

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

- 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 current FEH statistical method.

- Visual checks of each event were conducted noting whether the rainfall and flow event produce a hydrologically coherent event.

- 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.
4.3 Model calibration

Calibration of the events utilised the ReFH calibration software\textsuperscript{16} 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 ($B_L$, $B_R$, $T_p$ and $C_{\text{max}}$) for the catchment.

The calibration procedure is presented in full detail within Kjeldsen et al.\textsuperscript{17} In summary, $B_L$ and $B_R$ 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.

$T_p$ and $C_{\text{max}}$ 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 14 for each catchment considered.

\begin{flushleft}
\url{http://www.hydrosolutions.co.uk/products.asp?categoryID=4671}
\end{flushleft}

\begin{flushleft}
\end{flushleft}
### Table 14. Summary of the Calibration and Verification Datasets

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<thead>
<tr>
<th>NRFA ID</th>
<th>Catchment</th>
<th>Number of events</th>
<th>Calibration</th>
<th>Verification</th>
<th>Calibration Average percentage difference in Time to Peak</th>
<th>Peak Flow</th>
<th>Volume</th>
<th>Verification Average percentage difference in Time to Peak</th>
<th>Peak Flow</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>7001</td>
<td>Findhorn at Shenachie</td>
<td>12</td>
<td>11</td>
<td>-1.25</td>
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<td>0.23</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 5  Results for example catchments Enhanced Single Site Statistical Estimates and ReFH2 and ReFH1 for the ReFH model calibration catchments.

Parameters and Peak Flow Estimates for gauging stations which were used in the calibration of ReFH 2 that are within the NRFA Peak Flows dataset v.3.3.4 and are considered to be essentially rural (URBEXT2000 less than 0.03), a FARL value greater than 0.9, length of record greater than or equal to 14 years and suitable for QMED or pooling.
Appendix 6  Derivation of a revised $T_p$ equation for use within Scotland.

6.1 Introduction

Following the releases of versions 2.0 and 2.1 of the ReFH2 software the Scottish Environment Protection Agency identified that the Scotland Time to Peak ($T_p$) 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.

This Appendix describes the development of a new $T_p$ equation for ReFH 2.2 and above. This was developed using a larger set of catchments drawing additional catchments from the north of England. The patterns in the values of the $T_p$ parameter identified through calibration and the relationships with catchment descriptors were evaluated for the following catchment data sets:

- The ReFH 2 “Scotland only” catchment set (19)
- A new $T_p$ 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” $T_p$ equation within ReFH 2.

As stated, based on this analysis an alternative $T_p$ equation was derived using the Extended Scotland dataset and in consultation and agreement with the Scottish Environment Protection Agency this equation has been implemented within ReFH 2.2.

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

$$T_p = aPROPWET^{-b}DPLBAR^cDPSBAR^{-d}$$

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

6.2 Development of the “extended Scotland” catchment dataset

The key catchment descriptors that best explain the variation in $T_p$ across the UK are the $PROPWET$ (a characteristic representing likely catchment saturation), $DPLBAR$ (the mean drainage path length) and $DPSBAR$ (mean drainage path gradient) catchment descriptors. These descriptors, together with a consideration of catchment geology (using HOSTBFI) and geographic proximity were used to develop the Extended Scotland (ExtScot) dataset. Mean drainage path length is a more appropriate catchment scale descriptor than catchment area as it distinguishes between catchments on the basis of geometry as well as overall scale. For example, for a given
catchment area an elongated catchment will have a longer mean drainage path length than a catchment that is of a similar "length" and "width".

The variation in these descriptors across the Scottish catchments on the NRFA Peak Flows database (formerly HiFlows UK) was 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 EW&NI 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 15 present the minimum, maximum and median for each catchment descriptor for the different calibration datasets. For comparison these are also presented for the catchments within Scotland from the Peak Flows dataset used within the calibration of ReFH2 (99 catchments).

**Table 15. The minimum, maximum and median for each catchment descriptor for the calibration datasets and Scottish catchments within the Peak Flows dataset.**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>PROPWET</th>
<th></th>
<th>DPLBAR</th>
<th></th>
<th>DPSBAR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Median</td>
<td>Min</td>
<td>Max</td>
<td>Median</td>
</tr>
<tr>
<td><strong>Scotland Peak Flows</strong></td>
<td>0.3</td>
<td>0.9</td>
<td>0.6</td>
<td>2.1</td>
<td>87.4</td>
<td>21.3</td>
</tr>
<tr>
<td><strong>EW&amp;NI</strong></td>
<td>0.3</td>
<td>0.7</td>
<td>0.4</td>
<td>2.3</td>
<td>38.5</td>
<td>14.5</td>
</tr>
<tr>
<td><strong>Scotland</strong></td>
<td>0.5</td>
<td>0.7</td>
<td>0.64</td>
<td>1.6</td>
<td>54.5</td>
<td>16.6</td>
</tr>
<tr>
<td><strong>Extended Scottish dataset</strong></td>
<td>0.3</td>
<td>0.7</td>
<td>0.6</td>
<td>1.6</td>
<td>54.5</td>
<td>16.7</td>
</tr>
</tbody>
</table>

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.

6.3 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 25 to Figure 27 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 catchments that lie outside of the extended Scotland (ExtScot) data set are coded orange.
Figure 25 The Relationship between calibrated Tp values and PROPWET

Figure 26 The Relationship between calibrated Tp values and DPSBAR

Figure 27 The Relationship between calibrated Tp values and DPLBAR
The large values of $T_p$ 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 $T_p$ on catchment scale that is observed in the ReFH1 $T_p$ equation, the FSR $T_p$ equation and the ReFH 2 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 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 $T_p$ and catchment descriptors that are observed within the Scotland only data set.

### 6.4 Derivation of a $T_p$ equation using the ExtScot Dataset

The $T_p$ model was re-parameterised using the ExtScot catchment dataset. The implication for the estimation of $T_p$ values for catchments in the complete Scottish NRFA Peak Flows dataset is presented in Figure 28. The outlier station with a high $T_p$ when using the Scotland Equation is gauging station 20002 which is a small (low DPLBAR) dry (low DPSBAR and PROPWET) catchment.

![Figure 28. Tp values using the Scottish equation against Tp values using the EW&NI equation.](image)
6.5 Comparison of peak flows

The peak flows generated within ReFH 2 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 FEH13 rainfall model was used for this comparison work.

The comparison has been undertaken for estimates of QMED, the 1 in 2 year return period and the Q200, 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 Q200 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 Q200 between the at-site statistical estimates and the ReFH 2 estimates are presented in Table 16 together with bias corrected estimation of model FSE.

Table 16. 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 ReFH 2 models.

<table>
<thead>
<tr>
<th>Model</th>
<th>QMED (99 catchments)</th>
<th>Q(1:200) (87 catchments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFH2 FEH 13 rainfall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Bias</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scotland Tp</td>
<td>0.99</td>
<td>1.12</td>
</tr>
<tr>
<td>ScotExt Tp</td>
<td>0.87</td>
<td>0.97</td>
</tr>
<tr>
<td>Model FSE (bias corrected)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scotland Tp</td>
<td>1.33</td>
<td>1.46</td>
</tr>
<tr>
<td>ScotExt Tp</td>
<td>1.32</td>
<td>1.34</td>
</tr>
</tbody>
</table>

The results in Table 3 show that at QMED the new ScotExt Tp equation gives biased results for QMED (under-prediction on average) and fairly unbiased results at Q1:200 (noting the statistical estimates at Q200 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 ReFH 2 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 ReFH 2.2 for use within Scotland.