ReFH2 Science Report

Closing a Water Balance

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Contents

1 Introduction

ReFH2 models catchments as a rural area and an urban area, hence the model structure is comprised of a rural catchment model component and an urban catchment model component. The Percentage Runoff (PR) is considered as an area weighted sum of the contributions from the rural and urban parts of the catchment. The original ReFH 'as rural' model structure implemented in ReFH2.2 and earlier versions is not formulated to conserve mass. Similarly, the urban model implemented within ReFH2.2 (Kjeldsen et al., 2013)[1] is not constrained to conserve mass. Conservation of mass in hydrological modelling is commonly expressed as a volumetric water balance. That is, over a period of simulation the difference between the input and output fluxes of input rainfall and output stream flow and evaporation are equal to the change in the depth of water held within the model. If a model is mathematically constructed to conserve mass, the distribution of water between the output fluxes and storage within the model may not be correct but the water balance will be met. Within an event model, such as ReFH, there is the additional issue that the water balance may be violated either through the sum of outputs and change in storage being greater or less than the input rainfall.

New model structures have been developed to address these water balance issues and implemented in ReFH2.3 for the Design Application and the estimation of an observed event. The modelling of the rural and urban areas of the catchment is discussed in detail within Sections 2 and 3, together with the new model structures.

Within the Design Application, an estimate of a rainfall depth over a specified duration and frequency is used within ReFH2 to estimate the flood hydrograph corresponding to that duration and frequency. ReFH2 is used in conjunction with a Depth-Duration-Frequency (DDF) design rainfall model and a corresponding set of design initial conditions. Commonly referred to as the design package, this application can be applied to river catchments to inform fluvial flood risk or at the scale of a parcel of land to inform pluvial flood risk and drainage design.

The recommended DDF model for use with ReFH2 is the FEH13[2] model, which supersedes the original FEH99[3] DDF model. The development of the ReFH2-FEH13 design application and the benefits of using ReFH2 in conjunction with the FEH13 DDF model are discussed in the 'ReFH2 Science Report: Evaluation of Rural Design Event Model' (2019)[4].

Revising the model structure to address the water balance issues necessitates a revision of the 'as rural' ReFH design package. This revision is presented in detail within Section 4 for the rural model component. The revision to the model structure is not available for use with the legacy ReFH2-FEH99 design package.

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[1] Kjeldsen, T. R., Miller, J. D. and Packman, J. C., 2013. Modelling design flood hydrographs in catchments with mixed urban and rural land cover. Hydrology Research, 44 (6), pp. 1040-1057.
[2] Stewart EJ, Jones DA, Svensson C, Morris DG, Dempsey P, Dent J E, Collier CG, Anderson CW (2013) Reservoir Safety – Long return period rainfall. R&D Technical Report WS 194/2/39/TR (two volumes), Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme.
[3] Faulkner, D.S. 1999 Rainfall Frequency Estimation. Volume 2 of the Flood Estimation Handbook, Centre for Ecology and Hydrology
[4] Wallingford Hydrosolutions. 2019. ReFH2 Science Report: Evaluation of Rural Design Event Model. Available via https://refhdocs.hydrosolutions.co.uk/References/.

The BFIHOST catchment descriptor is a key explanatory variable within the ReFH2 design package equations. BFIHOST is a regression model that explains the variation in the Base Flow Index (BFI) estimated from gauged flows records across the UK by references to the variation in the Hydrology Of Soil Types (HOST) soil classes within these gauged catchments. BFIHOST has recently been revised[5] to address concerns regarding estimates of BFI in specific types of catchments. This revised BFIHOST catchment descriptor, BFIHOST19, has been used in this update to the ReFH2-FEH13 design package.

The default design package option within ReFH2.3 is the new water balance option, however the original (ReFH2.2) ReFH2-FEH13 design package can be selected, as can the legacy ReFH2-FEH99 option. Section 5 present a detailed comparison between the two ReFH2-FEH13 rural design package options across catchments within the NRFA Peak Flows database.

Default parameter estimates are suggested for the urban model. However, the urban model is a very flexible modelling structure and it is recommended that local survey data is used to refine default values for the parameters. The recommended default parameters have been revised to reflect both the changes to the urban model structure and the changes to the rural model structure and associated FEH13 design package. The revision of these parameter estimates is presented within Section 6.

2 The ReFH Rural Model

2.1 Rural Model Overview

A schematic of the rural model is presented in Figure 1. The ReFH rural model has three components:

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

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

[5] Griffin, A., Young, A.R. & Stewart, E.J. 2019. Revising the BFIHOST catchment descriptor to improve UK flood frequency estimates. Hydrology Research, in press.

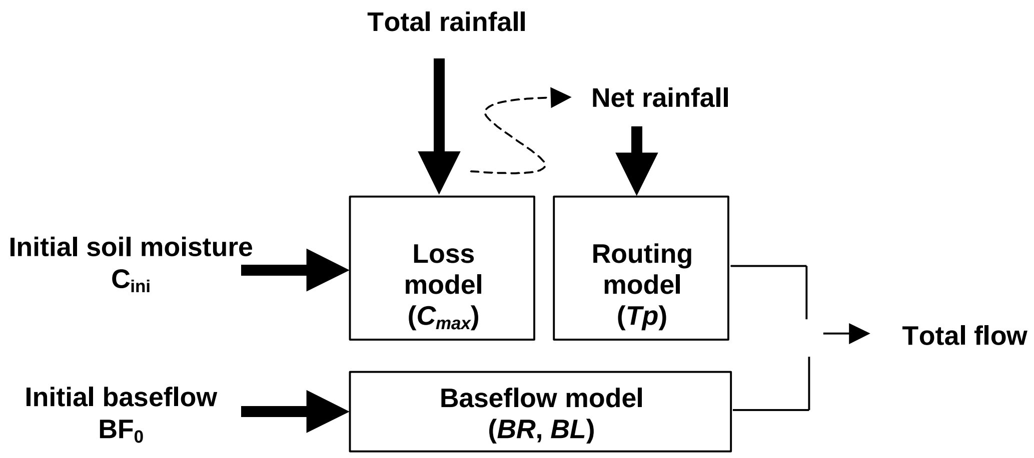


Figure 1. Schematic representation of the ReFH rural model

Table 1. Summary of the six ReFH model parameters

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

2.2 Water Balance Closure in the Rural Model

2.2.1 The Issue

It was originally envisaged that applications of ReFH would commonly involve calibrating the model parameters against a relatively small number of observed events. A ReFH Calibration Tool is available for download to enable users to undertake this calibration. It is notoriously difficult to reliably calibrate rainfall runoff models on small datasets due to the problems of equifinality. That is different combinations of model parameters may yield the same quality of fit in calibration but may give very different model outcomes when applied to new events. This problem scales with the number of parameters that have to be calibrated. As discussed in Kjeldsen (2007)[6] Sections 2 and 3.2, the BR and BL parameters are estimated directly from stream flow recession behaviour in the ReFH calibration strategy.

The water balance closure issue within the ReFH model framework is a consequence of this approach. Baseflow is estimated as a function of direct runoff, which is in turn a function of soil moisture status. This counter-intuitive model structure is elegant in that it facilitates the direct estimation of the base flow parameters from stream flow recession analysis leaving only two model parameters, C_{max} and Tp to be calibrated against observed event hydrographs. This enables reliable calibration of the ReFH model structure against a relatively small number of events. With four parameters in free calibration a much larger number of events would be required to obtain a reliable calibration.

If the catchment descriptor equations are used to estimate the model parameters, the model parameters are estimated independently from one another and the inherent relationship between the Baseflow Recharge (BR) and the C_{ini}/C_{max} ratio implicit within the calibration procedure is not maintained (where C_{ini} is the initial soil moisture content). This can result in a counter intuitive water balance violation where model generated baseflow and direct runoff depths can exceed the total event rainfall depth over events that are of the recommended duration or relatively close to the recommended duration and BR is greater than one.

Figure 2 presents a comparison of the estimation error in peak flow and the estimation error in event volume for 780 observed events drawn from 81 catchments. The estimates are those modelled using ReFH with calibrated model parameters and those when the model is used with the ReFH2 catchment descriptor estimates of the parameter values. In both cases the calibration estimates of C_{ini} (calculated from antecedent rainfall and potential evaporation data) are used and BF_0 is set to the first ordinate of the observed stream flow for the event in accordance with ReFH calibration guidance.

[6] Thomas Rodding Kjeldsen., 2007, 29. Supplementary Report No. 1. The revitalised FSR/FEH rainfall-runoff method. Centre for Ecology & Hydrology.

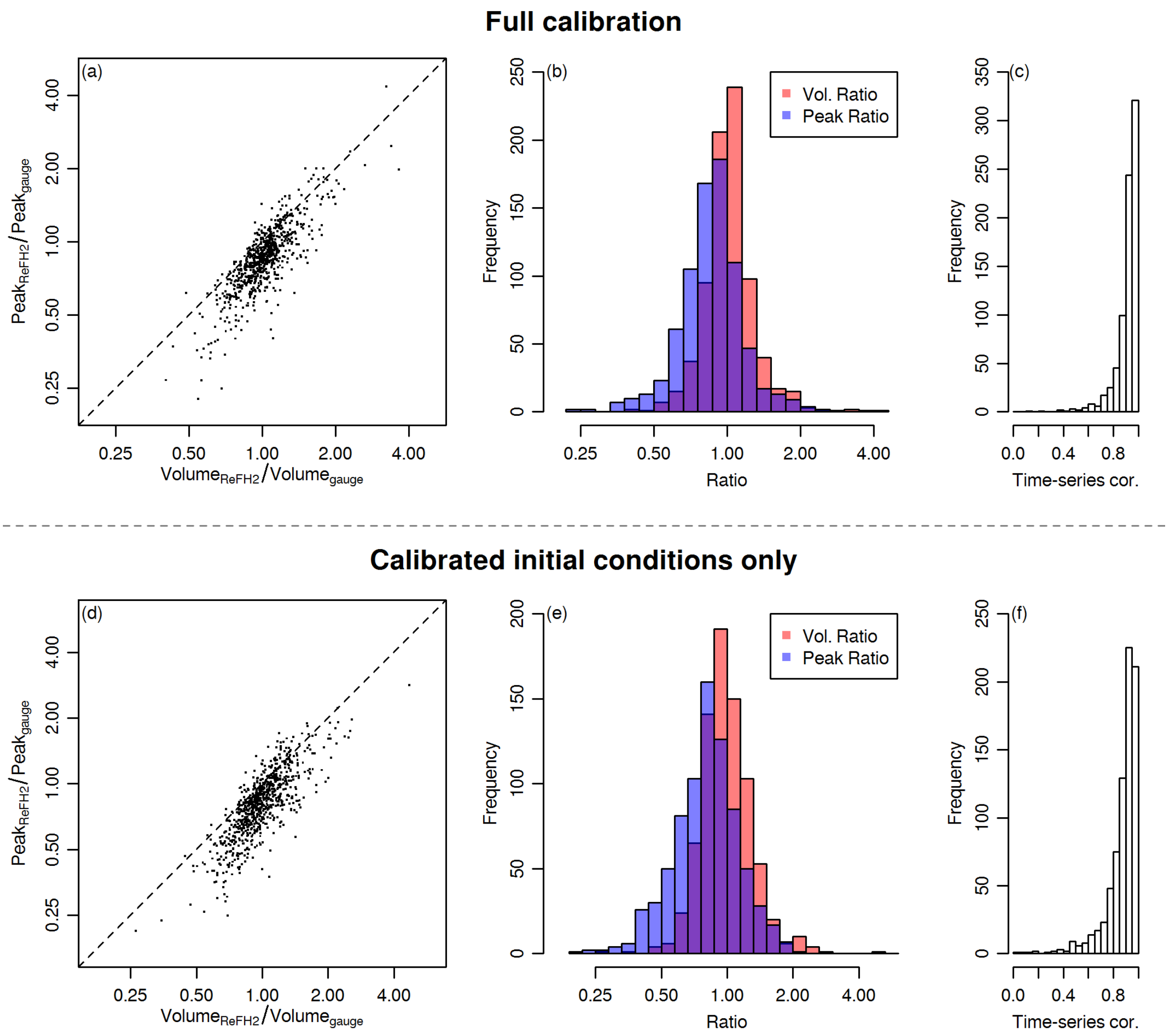


Figure 2 Scatterplot and histogram of over/underprediction in peak flow and runoff volume, and histogram of time-series correlation between observed and modelled hydrographs for ReFH2 model with full calibration of initial conditions and model parameters (a-c) and calibration of initial conditions only (d-f)

These results demonstrate a relatively small loss of model efficiency when the ReFH2 catchment descriptor based parameter estimates are used and furthermore there is a strong correlation between model performance in estimating peak flow and runoff volume. The objective function strategy within ReFH is to minimise the sum of squared differences between the simulated and observed ordinates of the hydrographs being modelled; an optimal value of zero would correspond to a perfect fit in terms of both volume and peak flow. It is reassuring that although the model structure is not formulated to close a water balance, the use of the catchment descriptor parameter estimates does not result in a large loss of performance in modelling either peak flow or event volume. That is, the model structure generally does not compromise the use of generalised model parameter estimates rather than calibrated model parameter estimates. However, in small very impermeable catchments and more generally when events of durations well in excess of the recommended duration are used, ReFH can violate a water balance with the simulated event depth exceeding the depth of the input hyetograph.

2.2.2 Addressing the Issue

This issue has been addressed within ReFH2.3 for the FEH13 design package and the observed event application by the following:

- specifying BR as a model state variable with the objective of closing a water balance over the recommended duration for impermeable catchments, and
- segmenting a model run into segments each with a maximum length equivalent to the recommended duration for the application.

These are described further in the following sections.

Setting BR as an internal state variable

In the ReFH2.3 FEH13 water balance option and observed event applications BR is dynamically calculated as to close a water balance over an event in impermeable catchments. In permeable catchments it is constrained to ensure the water balance cannot be violated through total runoff exceeding rainfall (noting that the ReFH model structure assumes initial baseflow will continue to recess in the absence of rainfall). In permeable catchments due to the presence of significant recharge to aquifers with long residence times, a water balance over an event using an event model is not a hydrologically realistic objective.

Considering a simulation event as a water balance then:

Equation 1

$$P - E - q - z \pm \Delta S = 0$$

where:

P = precipitation depth (after the Seasonal Correction (SCF) and Areal Reduction (ARF) factors have been applied);

E = the evaporation is the loss that might occur from the soil moisture store over the duration of the direct runoff event. As this is typically about a 1-3mm/d loss in summer and less than 1mm/day in winter this term can be ignored;

q = the direct runoff depth during the event;

z= the baseflow depth generated during the event; and

ΔS = change in storage within model between the start and end point of the model.

The ReFH model structure is an event model that (like the FSR model) is not formulated mathematically to conserve mass over an event. However, the change in storage within the model can be implicitly assumed to be zero if the simulated event is terminated when the baseflow after the event, z(t), has recessed to the initial condition, BF_0. As discussed, this is a reasonable assumption for impermeable catchments.

Under these assumptions Equation 1 simplifies to:

Equation 2

$$P - q - z = 0$$

Considering the BR parameter within the ReFH model structure, this is defined as:

Equation 3

$$BR = \frac{z}{q}.$$

Substituting Equation 3 into Equation 2 yields:

Equation 4

$$P - q(1 + BR) = 0$$

From geometric considerations of the ReFH loss model:

Equation 5

$$\frac{q}{P} = \frac{C_{ini}}{C_{max}} + \frac{P}{2C_{max}}$$

Where C_{ini} is the initial soil moisture content and C_{max} is the maximum soil moisture content as previously discussed.

Re-arranging Equation 4 and substituting Equation 5 for q, yields:

Equation 6

$$BR = \frac{1}{\left(\frac{C_{ini}}{C_{max}} + \frac{P}{2C_{max}}\right)} - 1$$

Thus, BR can be defined analytically at the start of a model run to close a water balance based upon the rainfall depth. The corollary of this is that as the magnitude of an event increases, the depth of both direct runoff and baseflow will increase, but a greater proportion of rainfall will form direct runoff. This is intuitively attractive from a hydrological perspective.

BR is defined using Equation 6 for catchments with BFIHOST19<0.5. As catchments become more permeable (between BFIHOST19 0.5 and 0.65), if the BR calculated from Equation 6 is greater than the BR estimated from catchment descriptors the BR is estimated as a weighted average of the value calculated using Equation 6 and the value of BR estimated from catchment descriptors. Above BFIHOST19 0.65, the BR value is based on the catchment descriptor estimate. As there is some evidence the BR catchment descriptor equation underestimates BR in permeable catchments, bounding values of the estimate plus one standard error are used. This ensures a water balance is closed within impermeable catchments and for more permeable catchments, where the water balance includes recharge to superficial or primary aquifers, BR is set to a value informed by the model performance in permeable catchments.

Modelling long duration events using segment models

In common with any model, ReFH has a calibrated model parameter space in application within a catchment. Significant observed events within a catchment are typically of a similar duration to the recommended duration and the model parameters are calibrated to these observed events. The catchment descriptor equations are based on the calibration of the ReFH model structure over a candidate set of catchments. The candidate parameter sets are entered into a multivariate regression to derive the model parameter catchment descriptor equations. These equations thus reflect the duration of the observed events within the candidate catchments used to define the parameter equations.

The issues with baseflow generation are discussed in the previous section. However, running the model for events that are significantly longer than the recommended duration within a catchment inevitably means that the model is being applied outside of the calibrated model range. The application of particularly long observed rainfall sequences can also result in unrealistically high runoff fractions for the latter part of the event. The reason for this is that the water content of the loss model is not adjusted to reflect the baseflow generated within an event. This is an issue for design events of duration much longer than the recommended duration. It is also an issue for long observed events where the duration of the event may be many multiples of the recommended duration with multi-modal peaks in the hyetograph.

This is addressed in ReFH2.3, for both the application of the FEH13 Water Balance design package and the Observed Event application, by subdividing the rainfall hyetograph (whether observed or design) into n segments of maximum length equivalent to the recommended duration. The model is then run for each segment.

The first segment is run using the initial C_{ini} and BF_0 conditions (design or specified through DAYMOD in the case of an observed event). At the end of each segment the baseflow depth generated within the segment is calculated. The soil moisture depth (SM) of the loss model at the end of the segment is then depleted by the depth of baseflow and a revised $C_{(t)}$ value is calculated. This value of $C_{(t)}$ forms the C_{ini} value for the second segment, and so forth for the remaining segments.

The model for each segment is runs with the final direct runoff hydrograph consisting of the sum of the direct runoff hydrographs for the individual segments. The baseflow model within ReFH is a linear model thus the baseflow for any timestep is the sum of the baseflow generated from all model segments operating within that timestep. The end of the event is defined as being the time step at which the total flow has returned to within 0.5% of the BF_0 or the last timestep for which there is direct runoff.

This updating of the soil moisture store at increments of the recommended duration ensures that the model cannot generate unfeasibly high runoff rates for events that significantly exceed the recommended duration. The baseflow depth generated during the first segment is generally relatively small and the model is generally operating within the calibrated model parameter space. Thus, the corrections for events that are less than, or equal to twice the recommended duration are minimal.

3 The ReFH2 Urban Model

3.1 Urban Model Overview

Urban areas are a mosaic of impervious and green (pervious) spaces as shown diagrammatically in Figure 3. Historically, impervious spaces were commonly positively drained by surface drains or combined sewers. Post 1950s developments are commonly served by separate foul sewers and surface water drainage. With the advent of SuDS, the focus of drainage design is now to mitigate at source and/or store impervious runoff for subsequent release at controlled rates. Some of the green spaces historically may also run off on to drained impervious surfaces, and thus may also be positively drained.

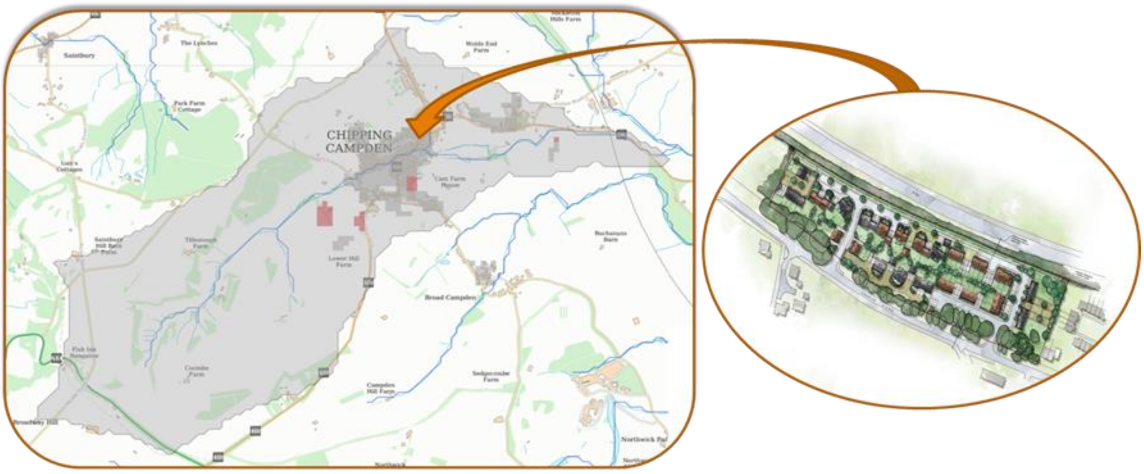


Figure 3 Urban catchments: a mosaic of green and impervious spaces.

It is generally accepted that an increase in urban extent hence impervious area should result in decreased infiltration capacity and surface storage, thereby increasing runoff volumes. At the same time the positive drainage of the impervious surfaces and green (pervious) spaces that drain to these surfaces will reduce catchment response time. The combination of these two effects will both increase the peak flows experienced in urbanised catchments and the fraction of total runoff that is direct runoff.

3.1.1 Modelling Nett Rainfall

The urban model published by Kjeldsen et al. (2013)[7] was used in ReFH2 up to and including ReFH2.2. In application, the catchment is modelled as separate urban and rural areas. The catchment Percentage Runoff (PR) is considered as a weighted sum of the contributions from the rural and urban areas of the catchment. The PR 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:

Equation 7

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

where $PR^{(rural)}$ is the percentage runoff from the rural area of the catchment and $PR^{(urban)}$ is the percentage runoff from the urban area. $URBAN_{50k}$ is the default estimate of the urban fraction of the catchment (as mapped on the Ordnance Survey 1:50K Land ranger map series).

Noting that $URBAN_{50k}$ can be estimated from URBEXT2000 using:

Equation 8

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

Focusing on the urban area, this is comprised of impervious areas and pervious (rural) areas. The model distinguishes between runoff generation from the pervious (rural) spaces within an urban area and the impervious surfaces. The fraction of the urban area that is impervious is defined by the Impervious Factor, IF, parameter. The pervious fraction by inspection is therefore (1-IF).

Thus within a time step, the Nett Rainfall for the urban area NR_{urban} consists of contributions from both impervious and pervious areas as:

Equation 9

$$NR_{urban}(t) = IF.NR_{impervious}(t) + (1 - IRF)NR_{pervious}(t);$$

The generation of nett rainfall from the pervious areas is modelled using the rural ReFH loss model. The nett rainfall from the impervious surface is assumed to be a fraction of the rainfall, P, incident upon the surface. This fraction, the Impervious Runoff Fraction (IRF) is a model parameter and thus NR_{urban} within a timestep is given by:

Equation 10

$$NR_{urban}(t) = IF.IRF.P(t) + (1 - IF)NR_{rural}(t);$$

[7] Kjeldsen, T. R., Miller, J. D. and Packman, J. C., 2013. Modelling design flood hydrographs in catchments with mixed urban and rural land cover. Hydrology Research, 44 (6), pp. 1040-1057.

3.1.2 Routing Model

For catchment applications, 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.[7] 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.

3.1.3 Baseflow Model

Within the ReFH2 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.

3.2 Water Balance Closure in the Urban Model

3.2.1 Modelling the Nett Rainfall

In the original work by Kjeldsen[7] it was assumed that (1-IRF) of the rainfall incident upon the catchment surface was held in storage and did not contribute to nett rainfall. The recommended default IRF is 0.7, and thus 0.3 of the incident rainfall is conceptually held on the catchment surface and doesn't contribute to runoff. For the modelling of the QMED event this would commonly be in the order of a centimetre of water and larger still for more extreme events. This is obviously unrealistic, but it is a modelling convenience that, as Kjeldsen identifies, dates back to early work on urbanised runoff conducted in the late 1970s and 1980s.

An alternative interpretation of the IRF parameter is that it can be regarded as the fraction of the impervious surface that is positively drained and that this drainage is assumed to be 100% efficient. The area of impervious surface that is not positively drained is then defined by (1-IRF). Clearly there will be an element of Depression Storage, DS (mm), across this area. Rainfall in excess of this storage will contribute to the pervious runoff within the urban area through percolation through cracks or edge run off and percolation. The Nett Rainfall from the urban area within a time step is given by:

Equation 11

$$NR_{urban}(t) = IRF.IF.P(t) + \big((1 - IF) + (1 - IRF).IF.DOF(t)\big).NR_{rural}(t);$$

Where:

NR_{urban} = nett urban rainfall

NR_{rural} = nett rural rainfall (from the ReFH2 rural loss model)

P(t) = incident precipitation; and

DOF = Depression Overflow Factor

Equation 12

$$if\ \sum_0^t P(t) - DS < 0,\ DOF(t) = 0$$

$$if\ \sum_0^t P(t) - DS > 1,\ DOF(t) = 1$$

$$if\ 0 < \sum_0^t P(t) - DS < 1,\ DOF(t) = \sum_0^t P(t) - DS$$

This revised urban loss model closes a water balance and is presented schematically within Figure 4. If DOF(t) is constrained to be 0 then this loss model simplifies to the original urban loss model of Kjeldsen et al[7]. This revised urban loss model is used if the default water balance closure option is selected for the FEH13 design package (the ReFH2.3 model).

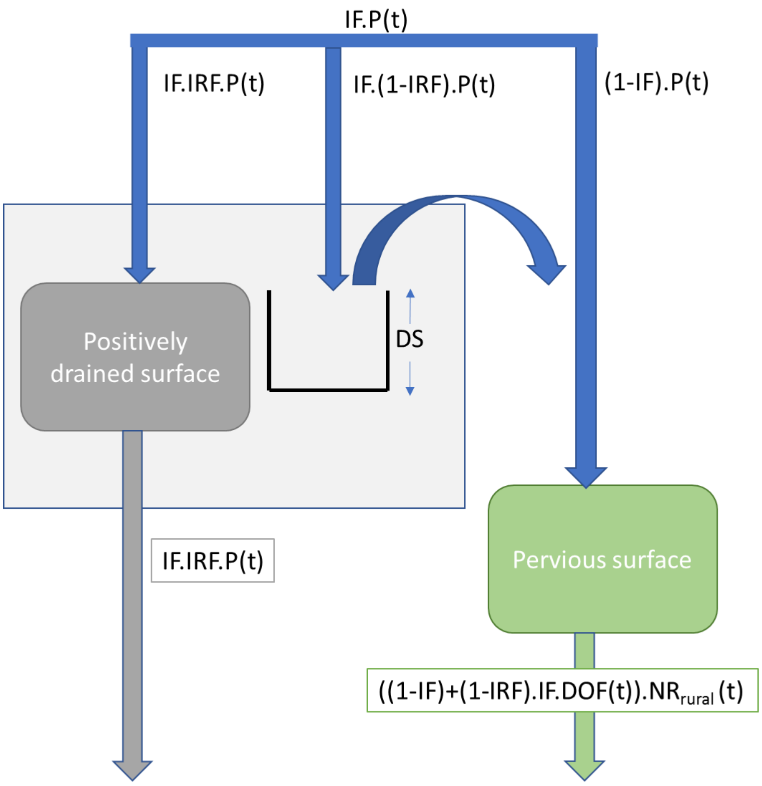


Figure 4 The ReFH2 urban area loss model closing a water balance

3.2.2 Routing Model

The routing model is unchanged. The revised nett rainfall from all contributing areas within the urban area are routed through the enhanced unit hydrograph as described within 3.1.2.

3.2.3 Baseflow Model

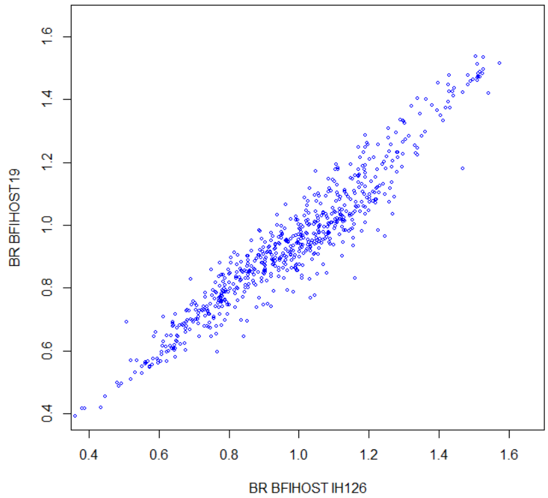
As discussed in Section 3.1.3, in the original urban model baseflow is not generated from the urban area, thus the model is not closing a water balance in this respect. Within the revised structure, implemented within the ReFH2.3 model, the pervious and non-positively drained impervious surfaces (once the depression storage has been met) generate baseflow using a transient estimate of direct runoff derived using with the original, as rural T_p as the basis for the estimation of this baseflow.

4 Revising the 'as rural' FEH13 design package

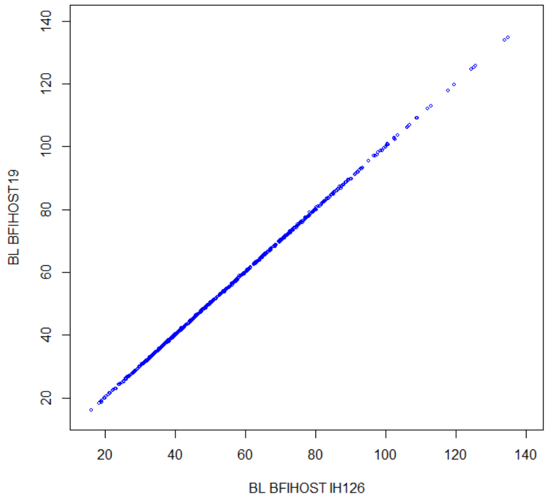
4.1 Substituting BFIHOST19 for BFIHOST in the ReFH2 Parameter Equations

The water balance revisions to the FEH13 design package have been developed using the BFIHOST19 catchment descriptor to take advantage of the improvements in this descriptor. BFIHOST is an explanatory variable in the parameter equations for BL, BR and C_{max}. Over the catchment datasets used to develop the parameter equations the differences between estimates generated using the two BFIHOST descriptors are not significant. Thus, the equations were not re-optimised for use with BFIHOST19.

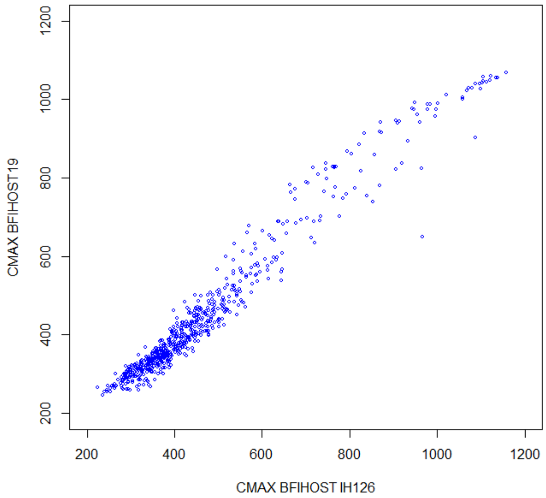
To gain a wider view, the same parameter estimates were generated for the catchments on the NRFA Peak Flows v7 dataset using both BFIHOST models. These estimates are compared on Figure 5 and show there are small differences between the estimates. Across this larger dataset, BR shows some tendency for the BFIHOST19 based estimates to be lower. This would intrinsically reduce the issue associated with water balance closure discussed when BR estimates are >1. BL is not very sensitive to the choice of BFIHOST. C_{max} tends to be lower for BFIHOST19 in very permeable catchments and higher in very impermeable catchments, which reflects the changes in BFIHOST as discussed by Griffin, et al[5].



(a) Baseflow Recharge, BR



(b) Baseflow Lag, BL



(c) Maximum Soil Moisture Capacity, C_{max}

Figure 5 Parameter estimate dependencies on the choice of BFIHOST model.

4.2 Development of revised rural C_{ini} models

The estimation of the initial depth of water held in storage in the catchment (C_{ini}) is a key component of the ReFH design package, which is discussed further in the 'ReFH2 Science Report – Model Parameters and Initial Conditions for Ungauged Catchments' (2019)[8]. For a given set of model parameters and rainfall event, a low C_{ini} results in a hydrograph with a smaller runoff volume and hence peak flows and, conversely, the hydrograph runoff volume and peak flow will be higher if C_{ini} is high.

The base C_{ini} estimate in the design package is a winter $C_{ini.}$ The ReFH2-FEH13 C_{ini} model was developed based on the estimation of the 1:2 Annual Exceedence Probability C_{ini}. The approach adopted used a subset of 680 catchments from the NRFA Peak Flow Dataset (version 7) for the analysis, which were flagged as:

- appropriate for the calculation of QMED,
- with more than 14 years of data (recommended for the calculation of QMED[9]),
- essentially rural (URBEXT2000<0.15); and
- as the impact of flood attenuation by reservoirs and lakes is not included within the ReFH model structure catchments with FARL<0.9 were also removed from the dataset.

The criteria for URBEXT2000 was updated from the previously used threshold of 0.03 (essentially rural) to a threshold of 0.15 to reflect the general findings of recent research[10] (Report 6). This research identified that the influence of urbanisation can only be detected for urbanisation levels above URBEXT2000 of 0.15. Note that the influence of urbanisation on QMED can be detected at lower levels of urbanisation in permeable catchments.

The following process was applied to each catchment:

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

[8] Wallingford Hydrosolutions. 2019. ReFH2 Science Report: Model Parameters and Initial Conditions for Ungauged Catchments. Available via https://refhdocs.hydrosolutions.co.uk/References/.
[9] Robson A & Reed D, 1999. Statistical procedures for flood frequency estimation, Flood Estimation Handbook Volume 3.
[10] Environment Agency, Estimating flood peaks and hydrographs for small catchments: Phase 2, Project: SC090031, *<Not yet published>*

Enforcing closure of a water balance through the choice of BR, whilst also yielding an estimate of the observed QMED through the choice of C_{ini} was generally achievable for catchments with BFIHOST19 values below 0.5 using the recommended duration. This could not be achieved in more permeable catchments, where QMED could only be estimated without error by reducing the value of BR and accepting that the sum of the direct runoff depth and baseflow depth is less than the observed rainfall depth. Thus, the values of C_{ini} and BR that replicated the observed QMED and maximised the sum of direct runoff and base flow were identified in these cases. It was also observed that in very permeable catchments, the BR values optimised in this way were extremely high giving rise to unfeasibly large baseflows.

These outcomes are consistent with the observation that effective rainfall contributing to baseflow can be retained in permeable catchments for long periods of time. This can range from months to years. The assumption of a closed water balance over an event is a reasonable assumption in impermeable catchments (low BFIHOST19), but is more questionable as the available storage within a catchment increases. It is certainly not a reasonable assumption in catchments with primary aquifer outcrops. This led to the introduction of the pragmatic upper limits set for BR as discussed in Section 2.2.2.

From the candidate catchment dataset, 25 catchments were removed (24 catchments, the same catchments as excluded in the development of the original ReFH2-FEH13 C_{ini} model, were excluded for water balance violations and 1 catchment removed due to hydrometric considerations). Catchments with water balance violations were identified as catchments for which both the ReFH optimal QMED estimate and FEH QMED catchment descriptor equation overestimated the QMED from the AMAX series by more than factor 3 or under-estimated by factor 0.33. As a secondary check, a comparison with a water balance estimate of gauged and mean flow estimated using the runoff grid method implemented within the LowFlows software (Holmes et al., 2002[11]) was also made. If this estimate was also in error, and in the same direction as the QMED estimates errors, the catchment was rejected on water balance considerations. This reduced the catchment data set to 655 catchments.

As in the original ReFH2-FEH13 design package, the optimised values were used to develop a generalised equation for the estimation of the normalised C_{ini} (defined as the ratio of C_{ini} to C_{max}). A linear relationship between the logarithms of the normalised C_{ini} and BFIHOST19 provided the best fit for the data. The form of this relationship is:

Equation 13

$$ln\left(\frac{Cini}{Cmax}\right) = a\ .BFIHOST19 + b$$

The relationship between modelled C_{ini}/C_{max} and BFIHOST19 is presented in Figure 6. The $\ln(C_{ini}/C_{max})$ estimates generated using this model are consistently lower than those for the original FEH13 design package, with the differences being larger in more impermeable catchments.

[11] Holmes, M.G.R., Young, A.R., Gustard, A.G. and Grew, R. 2002. A new approach to estimating mean flow in the UK. Hydrology and Earth System Sciences. 6(4), pp 709-720.

The summer C_{ini} is estimated as a function of the winter C_{ini} using the procedures detailed in the Environment Agency Project SC090031. The model obtained by re-optimising this model for both the water balance structure and the change to the use of BFIHOST19 yielded, in essence, the same model as used in the original FEH13 design package and so this element of the design package is retained.

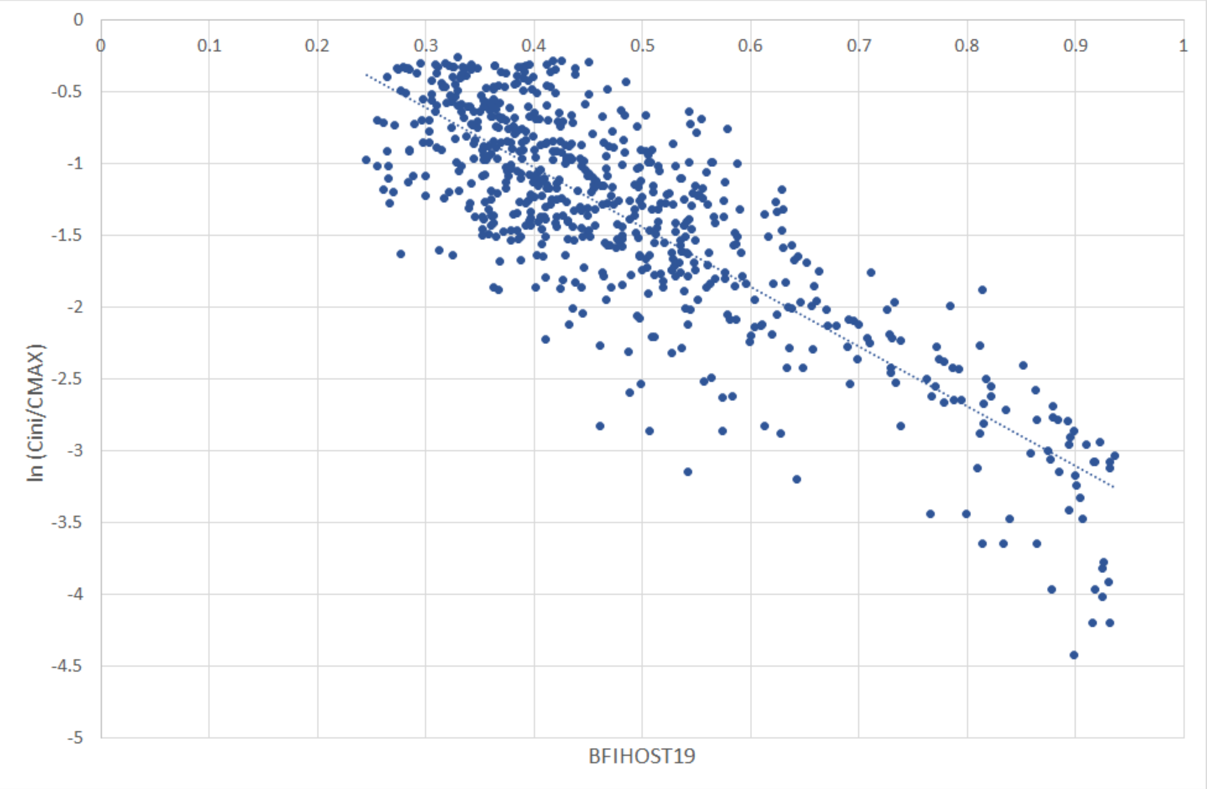


Figure 6 The relationship between the optimal C_{ini} and the BFIHOST19 value for the water balance design package

5 Estimation of design peak flows using the ReFH2-FEH13 water balance option

An extensive comparison analysis of the ReFH2-FEH13, ReFH2-FEH99, FEH statistical method estimates is presented within the 'ReFH2 Science Report: Evaluation of Rural Design Event Model' (2019)[4] and is not repeated here. A comparison of the water balance ReFH2-FEH13 (ReFH2.3) and the original ReFH2-FEH13 (ReFH2.2) estimates of QMED and the estimate of QMED derived directly from the gauged AMAX data are presented on Figure 7 for the NRFA Peak Flows v7 catchments used in this study. This shows the very close correspondence of the two estimates within these catchments. The QMED log residuals from the water balance model are plotted on Figure 8 as a function of catchment area (differentiated on permeability) and BFIHOST19 (differentiated on annual rainfall). These illustrate that the model is unbiased with reference to these descriptors.

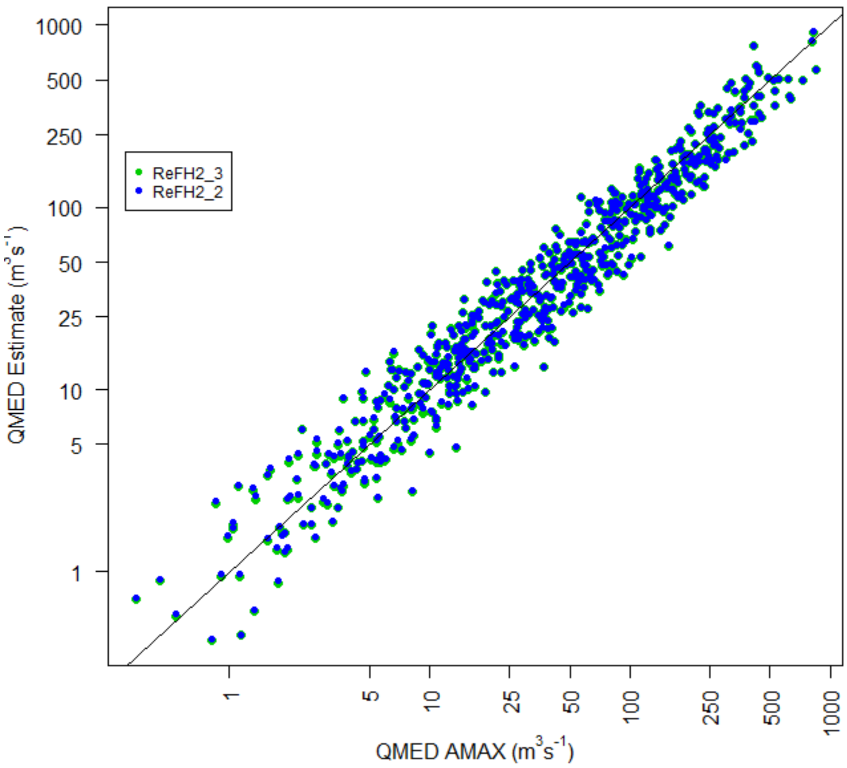


Figure 7 A comparison of QMED estimates generated using the two ReFH2-FEH13 design packages and QMED estimated from the gauged Amax series.

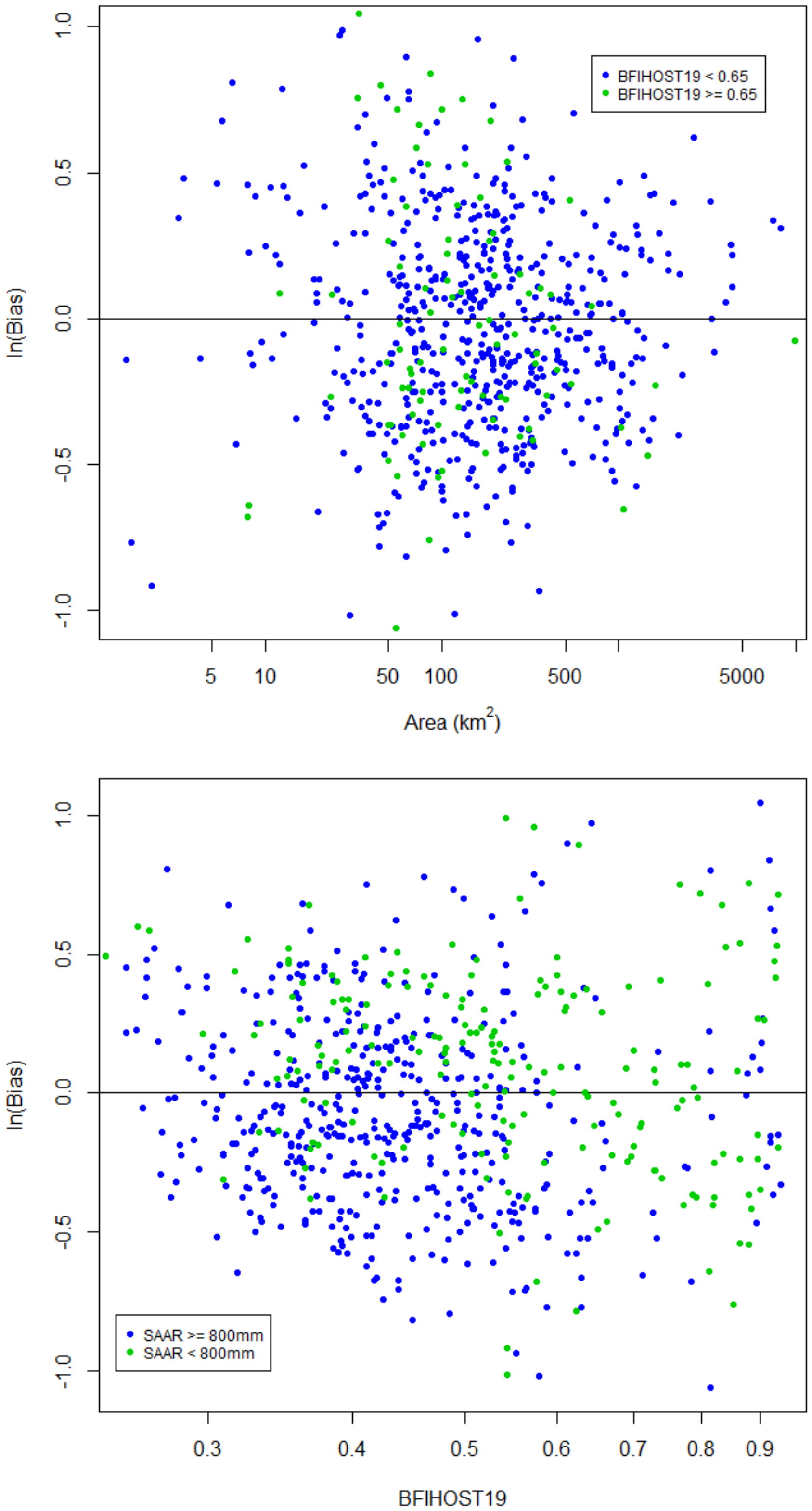


Figure 8 QMED model residuals for the ReFH2-FEH13 water balance design package

A comparison of the ReFH2-FEH13 design package estimates and the FEH pooled statistical estimates is presented on Table 2. The estimates are compared with the FEH Enhanced Single Site statistical estimates (ESS) using statistics of Bias, RMSE and FSE. For QMED this is a comparison with QMED estimated directly from the gauged AMAX series. For higher return period events the comparison is with the ESS growth curve rescaled by the AMAX series estimate of QMED. The FEH statistical estimates are the pooled growth curve estimates excluding the at-site data and rescaled by the catchment descriptor estimate of QMED. Although the values of bias and FSE differ slightly from those previous presented in the 'ReFH2 Science Report: Evaluation of Rural Design Event Model' (2019)[4] the basic patterns are the same. All three methods give very comparable estimated over all catchment meeting the selection criteria. The values differ slightly from the previously reported figures as a larger set of catchments is considered and the current version of the NRFA Peak Flows dataset has been used.

Table 2 Fit statistics for the estimation of QMED

		n	ReFH2-FEH13		FEH Statistical
			Water balance	Original	
Bias (%)	Q2	655	-2.71	-1.04	-6.49
	Q100	431	-0.43	0.13	-6.14
	Q200	431	2.24	2.83	-6.17
	Q1000	431	7.71	8.52	-6.26
RMSE	Q2	655	0.36	0.36	0.35
	Q100	431	0.39	0.39	0.38
	Q200	431	0.41	0.40	0.38
	Q1000	431	0.44	0.44	0.40
FSE	Q2	655	1.43	1.44	1.42
	Q100	431	1.48	1.48	1.46
	Q200	431	1.5	1.5	1.46
	Q1000	431	1.55	1.55	1.49

6 Default Parameters for Closing a Water Balance in an Urban Catchment

The changes to the treatment of urban runoff to account for depression storage and runoff from surfaces that are not positively drained requires a re-optimisation of the urban model to identify recommended default parameters. As discussed in the ReFH Technical Guide[13], these default parameters should be treated as initial values. If the analysis is sensitive to the choice of parameters, local data should be sought to revise the parameter values.

The approach adopted for the re-optimisation of the urbanisation model was based on identifying the optimal values of IF and the Tp multiplier required to minimise the ReFH2 model residuals for QMED estimation in urbanised catchments. The revised QMED estimates derived using the water balance design package configuration are used in this instance. The optimisation adopts the storm seasonality rules established for ReFH[10], that a summer storm should be used within ReFH2:

- If URBEXT2000 is ≥ 0.30, summer storms should be used;
- If 0.15 ≤ URBEXT2000 < 0.30 and BFIHOST19 is ≥ 0.65, summer storms should be used; and
- In all other cases winter storms should be used.

If a summer storm is selected using these rules, the summer C_{ini} is used together with the summer 50% profile. The 'ReFH2 Science Report – Model Parameters and Initial Conditions for Ungauged Catchments' (2019)[8] provides a summary of the summer and winter storm profiles. The optimal values of values of IF and Tp were identified by minimising the estimation bias for 52 catchments drawn used in the previous optimisation work with URBEXT2000 values greater than 0.15 and FARL > 0.9.

The IRF default value was retained as 0.7 since IF and IRF are covariant within the model and thus only one needs to be modified. In this application the recommended duration was based on the 'as rural' duration estimated from the 'as rural' Tp estimate and SAAR. An apriori estimate of 0.5mm of depression storage was identified as an appropriate default value based on a review of the literature, and one that is widely used in UK drainage design. This literature review is presented in Appendix 1.

As in the previous work, two classes of urbanisation were considered: 0.15 ≤ URBEXT2000 < 0.3 and URBEXT2000 ≥ 0.3. The rationale for the choice of these class boundaries is based on the seasonality rules: 0.3 is the threshold at which the seasonality analysis suggests that the largest flood events tend to be summer events in all catchments, and in the interval 0.15 ≤ URBEXT2000 < 0.3 the large events in permeable catchments tend to be summer events.

Following the structure of the previous optimisation work, the optimisation of the Tp multiplier and the IF parameter has focused on the heavily urbanised catchments ($URBEXT_{2000}$ ≥ 0.3). The absolute estimation bias results are presented for each scenario in Figure 9. The blue cells in these diagrams are estimates that are reasonably unbiased, grading to red cells in which the results are either biased strongly toward underestimation (lower left) and to overestimation (upper right).

[13] ReFH Technical Guide https://refhdocs.hydrosolutions.co.uk

The diagram shows the covariance of bias with the IF and the Tp Factor; IF increases the impervious runoff volume, whilst the Tp Factor influences the timing and peakedness of the corresponding urban hydrograph. Small values of Tp Factor result in a very peaked hydrograph with a peak occurring before that of the as-rural hydrograph from the remainder of the catchment. One can therefore achieve a similar level of bias for different combinations of the two. The optimal (minimum bias) solutions is given by a Tp Factor of 0.75 and an IF of 0.4. For comparison, the equivalent optimal values for the original (ReFH2.2) urban model were identified as a Tp Factor of 0.5 and IF of 0.3 (less impervious runoff volume).

The urbanised and rural estimates of QMED are plotted on Figure 10 as a function of QMED estimated from gauged record for the urbanised catchments. The plot illustrates the extent to which the urbanised model addresses the underestimation of QMED by the 'as rural' model in urbanised catchments.

	Impervious Fraction (IF)								
Tp Factor	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.25	6	23	39	55	70	84	99	113	127
0.5	14	2	9	19	30	40	50	60	70
0.75	22	14	6	2	10	18	25	33	40
1	29	22	15	9	3	3	9	15	21

Figure 9 Matrix of absolute bias illustrating the relationship between *IF*, *Tp* Factor and absolute bias (%)

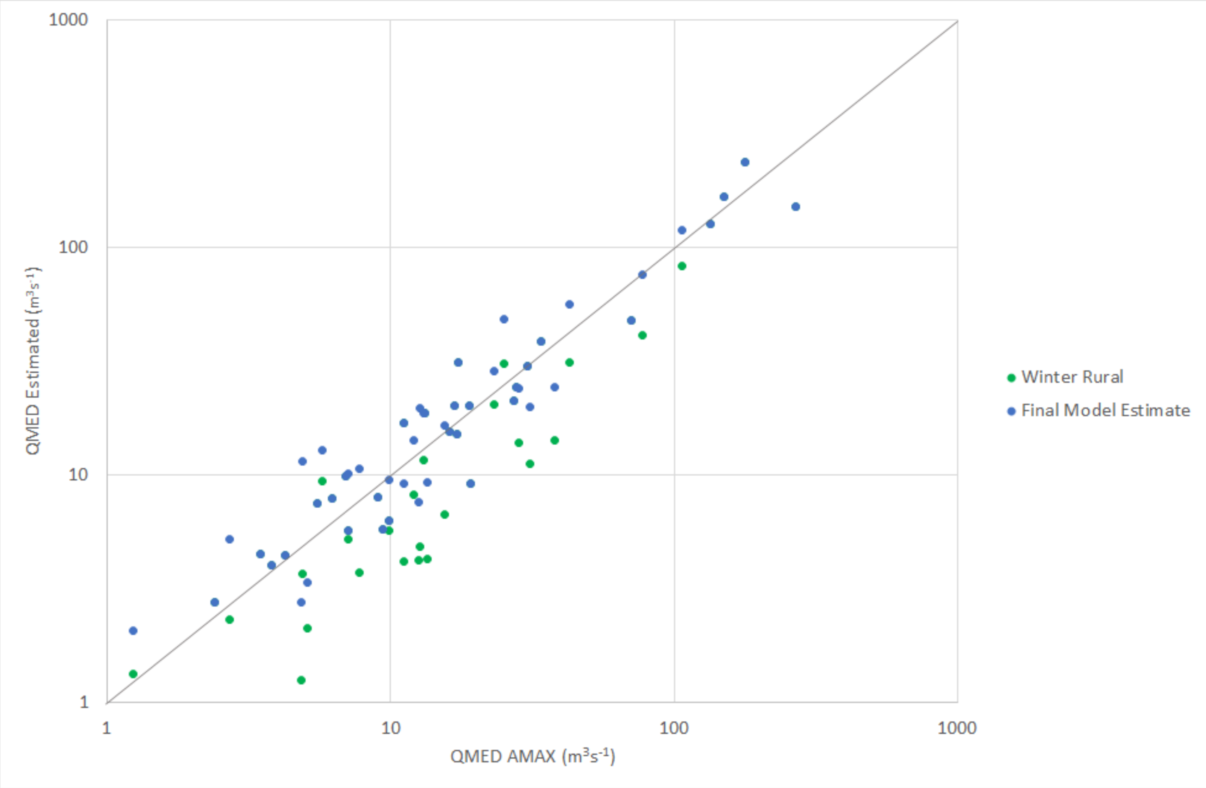


Figure 10 Urbanised model and winter 'as rural' model estimated of QMED compared with QMED estimated from gauged flow records for 52 catchments with URBEXT2000>0.15

Appendix 1 Depression storage and the concept of effective impervious area

1.1 Summary of ReFH2 Water Balance Urban Model

The conceptual model for the revised urban model is that the impervious surface defined by $IF.Area_{urban}$ can be subdivided into an area in which 100% of the rainfall is positively drained ($IRF.IF.Area_{urban}$) and an area of depression storage in which water is held on the catchment surface until the depression storage is filled and the precipitation in excess of this is assumed to contribute to the pervious part of the urban area. From this we can define new terms within the parlance of ReFH2:

- Total Impervious Area = $IF.\ Area_{urban}$;
- Effective Impervious Area (EIA) = $IRF.\ IF.\ Area_{urban}$; and
- Area of depression storage = $IF.Area_{urban}(1\text{-}IRF)$.

1.2 Effective Impervious Area

Ebrahimian et al (2016)[14] identified that the Effective Impervious Area (EIA), or the portion of total impervious area (TIA) that is hydraulically connected to the storm sewer system, is an important parameter in determining actual urban runoff. Using a semi-graphical method, called the successive weighted least square (WLS), they analysed the records from 50 urban catchments of different sizes and various hydrologic characteristics to determine EIA fractions and identified TIA fractions from cartography. The catchments varied from 0.01 km^2 to more than 20 km^2 in the USA states of Minnesota, Wisconsin and Texas, as well as Europe, Canada, and Australia. The average, median, and standard deviation of EIA fractions for the 42 catchments with residential land uses were found to be 0.222, 0.200 and 0.113, respectively and thus can be considered to be significantly urbanised. The equivalent values for the EIA/TIA ratios were 0.50, 0.48 and 0.21, respectively, although the variability was high suggesting that it may be difficult to generalise.

The origins of the IRF runoff coefficient used in ReFH2 date back to the work of Packman[15] who considered overall percentage runoff as the weighted sum of the percentage rural and impervious runoff, where rural runoff is defined using the original flood studies rural runoff equation and impervious runoff set at 70%. In fact, Packman identified an optimal value of 63% in his work, but adopted a value of 70% based on the earlier work of Kidd and Lowing[16]. In this earlier work a value of 70% was used as part of an equation for testing how percentage runoff should be calculated and whether an allowance for pervious runoff should be considered. Nevertheless, the value of 0.7 is well established as design parameter in UK urban hydrology.

By inspection, the ReFH2 IRF is equivalent to the EIA/TIA ratio and thus the default value of 0.7 is reasonable, as is a value of 0.63, but users should treat it as a parameter that can be refined in application.

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[14] Ebrahimian, A., Gulliver J.S. & Wilson B.N. (2016). Effective impervious area for runoff in urban watersheds. Hydrol. Process. 30, 3717–3729
[15] Packman, J., 1980. The effects of urbanisation on flood magnitude and frequency. Institute of Hydrology Report No 63. Wallingford, Oxfordshire. pp 117.
[16] Kidd, C. H. R. and Lowing, M. J. (1979) The Wallingford sub-catchment model. Institute of Hydrology Report 60, Wallingford UK. pp57.

1.3 Impervious Depression Storage

Impervious area depression storage is water stored in low points on the impervious surface. Commonly expressed as a depth (volume per unit area) depression storage is depleted by evaporation in the absence of rainfall. During an event this storage will fill and spill once full.

Nehls et al (2013)[17] used a terrestrial laser scanner to undertake high-resolution surveys of 11 typical pavement designs and found that the surface depression storage varied from 0.07 to 1.4 mm. The authors recognised that, in practice that depression storage may be significantly higher as the initial surface wears, creating deeper puddles and cracks.

Boyd et al (1993)[18] graphically examined rainfall and runoff depths for 763 storms on 26 urban basins located in 12 countries. Plots of rainfall and runoff depths were used to estimate the effective impervious area and the impervious area initial loss. The data plotted close to a single straight line on all basins, indicating that the effective impervious area remained constant for all storm sizes. The effective impervious fraction was related to total impervious area and that directly connected impervious fraction estimated from maps. The initial storage loss (depression storage and interception storage) was estimated as zero in 11 catchments, with a maximum depth of 6.12 mm and the average depth over the 15 non zero catchments was 1.39 mm.

A functional relationship for mean depression storage, d (cm), across generic urban land cover was derived based on slopes by Kidd (1978)[19], as an exponential decay function based on the area's slope, S (expressed as a percentage), with data from Holland, United Kingdom, and Sweden fitting with a correlation coefficient of 0.85:

$$d = 0.077S^{-0.49}$$

In the United States Viessman et al., (1977)[20] used data from small impervious areas near Baltimore, Maryland and constructed a linear relationship for depression storage d (cm), based on percent watershed slope, S, by:

$$d = 0.341 - 0.076S.$$

Endreny (2006)[21] cites depression storage depth for various land cover types, citing 2-4 mm for large paved areas, 3-8 mm for flat roofs and 2-3 mm for pitched roofs.

At the catchment scale, Skotnicki and Sowiński (2013)[22] investigated the depression storage in a small (6.7 km^2), heavily urbanised (29% impervious) catchment in Poznan, Poland. The authors analysed 46 events over the period 2006-2010 using the SWMM 5 model and obtained the best simulation results using a depression storage depth of 1.5 mm. The spatial distribution of depressions was not found to have a significant effect on the shape of the computed hydrographs.

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[17] Nehls T., Menzel M. & Wessolek G. (2015) Depression storage capacities of different ideal pavements as quantified by a terrestrial laser scanning- based method. Water Science & Technology 71(6). pp. 862-869.
[18] Boyd M. J., Bufill M. C. & Knee R. M. (1993). Pervious and impervious runoff in urban catchments, Hydrological Sciences Journal, 38:6, 463-478,
[19] Kidd C.H.R. (1978) Rainfall-Runoff Processes Over Urban Surfaces, Institute of Hydrology, Proceedings International Workshop: Wallingford.
[20] Viessman J.W., Knapp J.W., Lewis G.L. and Harbaugh T.E. (1977) Introduction to Hydrology, Harper and Row: New York.
[21] Endreny T.A., 2005. Land use and land cover effects on runoff processes: urban and suburban development. M.G. Anderson (Ed.), Encyclopedia of Hydrological Sciences, John Wiley & Sons Ltd., Chichester, UK (2005), pp. 1775-1804
[22] Skotnicki M. & Sowiński M. (2013). The influence of depression storage on runoff from impervious surface of urban catchment. Urban Water Journal. Volume 12, 2015 - Issue 3, pp 207-218

The work of Kidd has been widely adopted in the UK through the Wallingford Procedures and various drainage software and is used to scope the setting of depression storage within ReFH2. The depression storage relationships of Kidd[19] and Viessman et al.[20] are graphed on Figure 11 (in the original units of inches). By inspection for slopes about 1% depression storage is typically around 0.02", that is 0.51mm. The UK data within the dataset used to develop the relationship are between 1% and 3%.

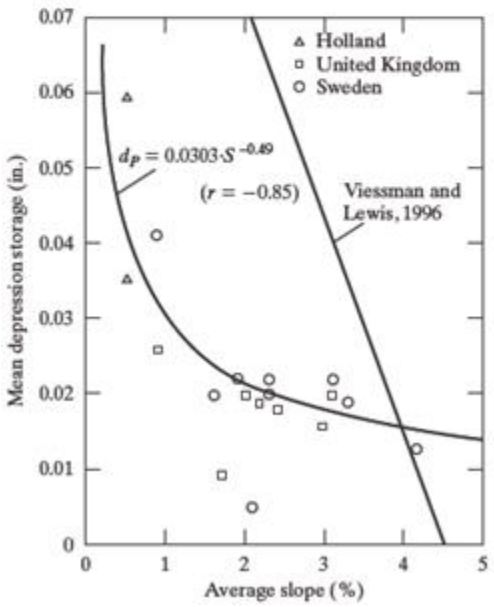

Figure 11 Depression storage vs catchment slope (after Kidd, 1978, Viessman et al 1996)

A user editable default of 0.5 mm for depression storage has been adopted in ReFH2.