FLOOD ESTIMATION HANDBOOK

Supplementary Report No. 1

Thomas Rodding Kjeldsen

The revitalised FSR/FEH rainfall-runoff method

Centre for Ecology & Hydrology

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Thomas Rodding Kjeldsen

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Preface

The research described in Flood Estimation Handbook Supplementary Report No. 1 was undertaken at the Centre for Ecology & Hydrology, Wallingford, Oxfordshire.

Contributors

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The Project Steering Group: Paul Webster (Hydro-Logic Ltd), David MacDonald (Black and Veatch) and Peter Spencer (Environment Agency).

Notation

The following are the main symbols and abbreviations used throughout this report. Other symbols have just local meaning and are defined where they occur. All units are metric except where otherwise stated.

ARF	Areal reduction factor
API5	5-day antecedent precipitation index (mm)
AREA	Catchment area (km^2)
BF	Baseflow (m^3s^{-1})
BF_0	Initial baseflow (m^3s^{-1})
BL	Baseflow recession constant (or lag) (hours)
BR	Baseflow recharge
C_{ini}	Initial soil moisture content (mm)
C_{max}	Maximum soil moisture capacity (mm)
CWI	Catchment wetness index (mm)
D	Duration of rainfall event (hours)
DDF	Depth-duration-frequency
DK	Daily soil moisture decay rate
DPLBAR	Mean drainage path length (km)
DPSBAR	Mean drainage path slope (m km^{-1})
FC	Field capacity (mm)
FEA	Flood Event Archive
FEH	Flood Estimation Handbook
FSR	Flood Studies Report
HiFlows-UK	Database of flood peak flow series for UK gauging stations
HOST	Hydrology of Soil Types (soil classification)
IHDTM	Integrated Hydrological Digital Terrain Model
IUH	Instantaneous unit hydrograph
MORECS	Met. Office Rainfall and Evaporation Calculation System
OLS	Ordinary least square
P	Total rainfall depth (mm)
PDM	Probability Distributed Model
PRESS	Predicted error sum of squares
PROPWET	Proportion of time when SMD was less than or equal to 6 mm during the period 1961-90.
q	Direct runoff (m^3s^{-1})
Q	Flow (m^3s^{-1})
ReFH	Revitalised Flood Hydrograph model
S	S-curve
SAAR	Standard average annual rainfall (1961-90) (mm)
SCF	Seasonal correction factor for d-hour/day rainfall
SM	Mean soil moisture depth (mm)
SMD	Soil moisture deficit (mm)
SPR	Standard percentage runoff (%)
SPRHOST	SPR derived from HOST soil classification (%)
T	Return period (years)
Tp	Unit hydrograph time to peak (hours)
u	Unit hydrograph response
UH	Unit hydrograph

U_k	Degree of kink in the standard unit hydrograph
$URBEXT_{1990}$	Extent of urban and suburban land cover (year 1990)
U_p	Unit hydrograph peak
w	Weight
WLS	Weighted least square

Chapter 1 Introduction

1.1 Background

This report is a key element in the Environment-Agency funded project (SC040029) to disseminate the revitalised FSR/FEH rainfall-runoff method. In addition to this report, two independent software packages have been developed to support the use of the method. Further details of the software can be found on the CEH website *http://www.ceh.ac.uk/refh*.

Although the FSR/FEH rainfall-runoff method was originally conceived during the research that led to publication of the Flood Studies Report (FSR) (NERC, 1975) more than 30 years ago, it continues to be widely used alongside statistical methods of flood frequency where estimates of complete flood hydrographs or total flood volumes are required. The method can be used to estimate the total flow from any rainfall event, whether it is an observed event or one that is statistically derived (a design storm). With the publication of the Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) came the introduction of new design inputs to the method, although the form of the underlying model remained largely unchanged.

For some time, users of the rainfall-runoff method have been making critical observations about the existing procedures and have highlighted a number of areas for improvement. Some of these relate specifically to reconciling possible anomalies that emerged following the adoption of FEH methods, but others raise more fundamental issues about the structure of the original model.

The revitalised FSR/FEH rainfall-runoff method has been developed as a replacement to the method described in Vol. 4 of the FEH (Houghton-Carr, 1999). The revitalised method introduces improvements to the key components of the rainfall-runoff method, taking advantage of new data, updated analytical techniques and advances in computation. In particular, the method has improved the description of the hydrological processes underpinning the rainfall-runoff method. The development of the method also benefited from the use of many of the relatively large flood events recorded in recent years.

1.2 Development of event-based rainfall-runoff models for hydrological design

Rainfall-runoff models for design flood estimation have been used by engineers and hydrologists for more than a century. During this time, the methodologies have evolved, reflecting increases in computing power, improvements in available analytical techniques and steadily increasing data records. Since 1975, the rainfall-runoff method published as part of the FSR has been central to design flood estimation in the UK. The method was subsequently updated and improved through a series of FSR supplementary reports (Institute of Hydrology, 1977; 1979; 1983; 1985) and Institute of Hydrology Reports (Marshall and Bayliss, 1994; Boorman *et al.*, 1995 and Boorman *et al.,* 1990).

In its simplest form the FSR rainfall-runoff method has three main parameters: unit hydrograph time to peak (*Tp*), percentage runoff (*PR*) and baseflow (*BF*). Through the analysis of a large number (1488) of observed flood events, the model parameters were estimated for 143 gauged catchments in the UK. Using multivariate linear regression techniques, the model parameters were linked to mapped catchment characteristics thereby providing a means applying the rainfall-runoff model at ungauged sites throughout the UK. To allow estimation of *T*-year events using the rainfall-runoff model, a depth-duration-frequency (DDF) model was published as part of the FSR. A simulation study was carried out specifying combinations of antecedent soil moisture condition (*CWI*) and the return period of the design rainfall needed to produce flood hydrographs with a specified return period.

Following the continued updating of the FSR method and the availability of digital catchment descriptors for all drainage areas in the UK larger than 0.5 km^2 (Bayliss, 1999), the rainfall-runoff method was updated as part of the FEH analysis (Houghton-Carr, 1999). The updated method focused mainly on incorporating the new digital catchment descriptors into the method and the use of a new rainfall depth-duration-frequency (DDF) model also developed as part of the FEH. The FEH update did not change the underlying design package developed in the original FSR study and the version published in the FEH is referred to here as the FSR/FEH rainfall-runoff method.

The FSR/FEH rainfall-runoff method was in general found to yield larger estimates of *T*-year floods than when combined with the FSR DDF model, as reported by Spencer and Walsh (1999) for a case study of 36 catchments in north-west England and later by Ashfaq and Webster (2002) in a study of 88 catchments throughout the UK. The original FSR design model was calibrated using the FSR DDF model, and many practitioners believe that the combination of the FSR design model with the FEH DDF model results in design floods of excessive magnitude. In addition, Webster and Ashfaq (2003) found that the FSR/FEH design values of antecedent soil moisture and percentage runoff did not align well with the observed values in flood events from 206 UK catchments. Consequently, Defra and the Environment Agency initiated a project, aiming to revitalise the FSR/FEH rainfall-runoff model and to bring the different model components into a common framework for use in practical design flood estimation in the UK (Kjeldsen *et al.*, 2006).

1.3 The Revitalised FSR/FEH design method

The revitalised FSR/FEH rainfall-runoff method described in this report is based on the Revitalised Flood Hydrograph (ReFH) rainfall-runoff model.

This model has been developed to improve the way that observed flood events are modelled and has a number of advantages over the FSR/FEH unit hydrograph and losses model. The key improvements are:

- a new baseflow model which provides a more objective method of separating total runoff into baseflow and direct runoff;
- a loss model based on the uniform PDM model of Moore (1985);
- a more flexible unit hydrograph shape; and
- improved handling of antecedent soil moisture conditions.

For users with comprehensive experience of using the FSR/FEH method it is important to note that the ReFH design method is based on a parametric hydrological model which takes into account the interaction between direct runoff and baseflow. This is considered to provide a more realistic representation of the flood hydrology than that in the FSR/FEH method, where direct runoff and baseflow are treated as independent components.

1.4 Guide to this report

This FEH supplementary report presents the background to and describes the application of the revitalised FSR/FEH rainfall-runoff method. The report is intended to form a supplement to the existing five volumes in FEH, but does not replace any of them. The structure of this report is outlined below.

Chapter 2: The revitalised flood hydrograph (ReFH) model

This chapter provides a description of the structure of the ReFH rainfall-runoff model, which has been developed as an alternative to the FSR/FEH unit hydrograph and loss model described in FEH Vol. 4 (Houghton-Carr, 1999). The content of this chapter gives an overview of the ReFH model, with more detailed descriptions of some of the model components contained in the accompanying appendices.

Chapter 3: ReFH model parameter estimation

The ReFH model parameters can be estimated either through analysis of observed events at gauged sites or, at ungauged sites, through the use of catchment descriptor-based predictor equations. A discussion of the use of donor sites offers assistance on estimating model parameters at ungauged sites through information transfer from gauged sites to ungauged sites.

Chapter 4: *T*-year flood estimation

This chapter describes the application of a procedure for generating design flood hydrographs using the ReFH model. The method requires a design rainfall event to be specified along with a design value of the initial soil moisture content. Each input parameter in the design procedure is explained and examples of application are provided for each step. The background and development of the procedure are outlined in Appendix D.

Chapter 5: Application – considerations and limitations

This chapter discusses practical aspects of applying the ReFH model and highlights issues where the revitalised FSR/FEH rainfall-runoff method is likely to be used but where no specific research has been conducted at present. The issues include: return period assessment of notable flood events, probable maximum flood estimation, reservoir routing, disparate subcatchments and land use effects.

Chapter 6: Worked examples

This chapter contains two examples of the application of the revitalised FSR/FEH rainfall-runoff method. In the first example, a 100-year design flood is generated, and in the second a notable observed flood event is simulated.

References

Appendix A: The ReFH loss model

Appendix B: The ReFH antecedent soil moisture accounting model

Appendix C: ReFH model parameters for 101 catchments.

Appendix D: Calibration of the ReFH design method

Chapter 2 The Revitalised Flood Hydrograph (ReFH) model

2.1 Introduction

Rainfall-runoff modelling for design flood estimation has conventionally been based on the modelling of individual events. At the most rudimentary level all that is required to reproduce the catchment-scale relationship between storm rainfall and the corresponding stream flow response is

- a volumetric loss to account for hydrological processes such as evaporation, soil moisture storage, groundwater recharge and interception losses; and
- a time distribution model to represent the various dynamic modes of catchment response.

However, the specification of the model developed to represent the rainfall-runoff relationship is very much related to scale, both spatial and temporal. For instance, a model relating the annual rainfall and runoff for a small homogeneous catchment may be very simple, while the relationship between hourly rainfall and runoff on a large, heterogeneous catchment may be extremely complex. This ability to lump together various hydrological processes rather than explicitly include them and to identify and isolate the event response, together with the simplicity of model application, accounts for the widespread use of the FSR/FEH approach to event-based modelling. The Revitalised Flood Hydrograph (ReFH) model has been developed for use in the revitalised FSR/FEH rainfall-runoff method as a parameter-sparse hydrological model, representing the major rainfall-runoff processes on a catchment scale.

In the following it is important to distinguish whether the ReFH model is used for modelling an observed flood event or for generating a design flood event. When modelling an observed event, the ReFH model is used as a deterministic model trying to reproduce a flood event from historical series of observed rainfall and soil moisture data. In contrast, a design event is a probabilistic estimate of a flood event that will be exceeded on average once every T years, where T is the return period (e.g. $T = 100$ years). When generating a design event (see Chapter 4), the input values of rainfall and antecedent soil moisture do not represent a particular historic event but are generalised values specified so that certain combinations will result in a flood event of the required return period.

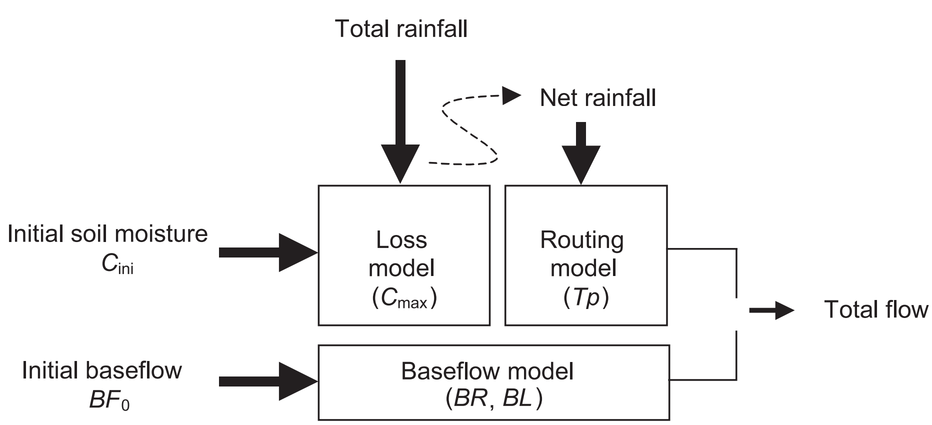


Figure 2.1 *Schematic representation of the ReFH model*

2.2 Modelling concept

The ReFH model consists of three main components: a loss model converting total rainfall into effective rainfall, a routing model and a baseflow model. The connections between the three model components are shown in Figure 2.1 together with the required input variables and model parameters. In addition to the three main components, a soil moisture accounting model based on daily data is used to determine the state of the soil at the start of the flood event based on long-term series of antecedent rainfall.

When simulating a flood event, the loss model is used to estimate the fraction of the total rainfall volume turned into direct runoff. The direct runoff is then routed to the catchment outlet using the unit hydrograph convolution in the routing model and, finally, the baseflow is added to the direct runoff to obtain total runoff. Each of the three components, including the various model parameters, will be further explained further in the following sections.

2.3 Loss model

The loss model in ReFH is based on the Probability Distributed Model (PDM) developed by Moore (1985) and widely used for a variety of hydrological applications in the UK. The PDM model is being used in a framework for a national system for flood frequency estimation using continuous simulation modelling in the UK (Lamb, 1999; Calver *et al.*, 2005). Furthermore, the model has been used in real-time flood forecasting (Moore, 1999) and it has been used to investigate the impact of climate change on runoff from small catchments in the UK (Prudhomme *et al.*, 2003).

Conceptually, the PDM assumes the catchment to consist of a number of individual storage elements, each of a random soil moisture capacity C arising from a statistical distribution. Assuming a uniform distribution of soil moisture capacities, if the storage elements are arranged in order from the highest (C_{max}) down to zero capacity, the resulting PDM distribution of soil moisture capacity is shown in Figure 2.2, where the horizontal axis represents the cumulative distribution. It is further assumed that the storage elements interact such that the soil moisture is redistributed between stores between rainfall events. Thus, at any time soil moisture is constant for all elements of capacity greater than C_t and is at full capacity for elements of capacity smaller than C_t as illustrated by the dark grey area in Figure 2.2. During a storm, the depth of water in each storage element is increased by rainfall (light grey area) and when rainfall exceeds the storage capacity, direct runoff is generated. For the short duration of the storms under consideration, the effects of evaporation and drainage out of the soils have not been included.

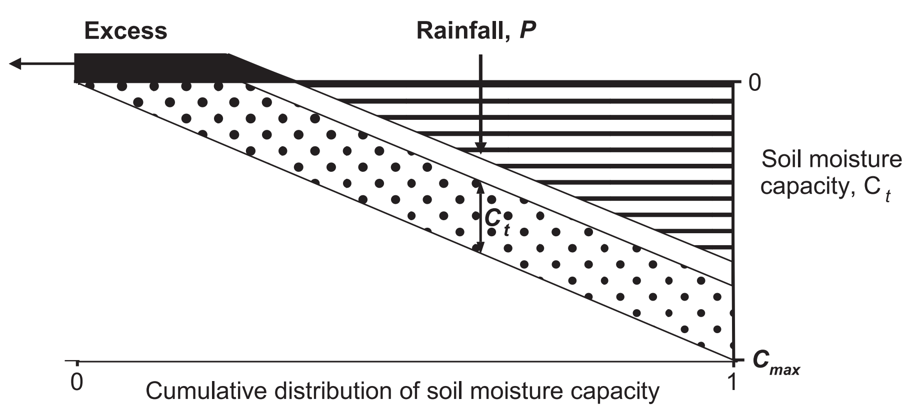


Figure 2.2 *Equal water content C_t across stores of different capacity*

Thus, a pulse of rain, P_t, on the soil gives 100% runoff from the area already at full capacity and increases the moisture content in all other areas. The excess amount of rainfall converted into direct runoff, q_t, can be estimated through simple geometric considerations as

$$\frac{q_t}{P_t} = \frac{C_t}{C_{\max}} + \frac{P_t}{2C_{\max}} \qquad \text{for } t = 1, 2, 3, \ldots \tag{2.1}$$

where the continuity equation $C_{t+\Delta t} = C_t + P_t$ applies and C_{ini} is the soil moisture content at the start of an event. The ratio q/P of rainfall transformed into direct runoff is a measure of the percentage runoff, and C_{max} is the only model parameter. Once C_t exceeds C_{max}, the model assumes that 100% of the rainfall is converted into runoff. The derivation of Equation 2.1 is shown in Appendix A. The loss model can be applied sequentially, where a loss is calculated for each time step, or it can be applied to calculate a single loss of total rainfall volume. In the revitalised FSR/FEH rainfall-runoff method, the former option has been adopted, i.e. a loss is calculated for each individual time step. As the soil becomes increasingly wet during the storm, the loss decreases and the runoff rate increases.

The initial soil moisture content (C_{ini}) is an important parameter when applying the loss model, either for analysing an observed event or for simulating a design flood event. The method for obtaining an estimate of C_{ini} is different for the two cases (observed or design flood event) and each case will be analysed in subsequent sections (observed event §3.2.6 and design event §4.5).

2.4 Routing model

The ReFH model uses the unit hydrograph (UH) concept for routing the net rainfall to the catchment outlet (direct runoff). A UH can be estimated directly for each flood event through simultaneous analysis of the effective rainfall hyetograph and the direct runoff hydrograph as described by Chow *et al.* (1988), for example. The original FSR/FEH model adopted a standard triangular-shaped instantaneous unit hydrograph (IUH) scaled to each catchment using the time-to-peak (*Tp*) parameter, catchment area and the selected time step. The ReFH model retains the concept of a standard IUH shape scaled to individual catchments, but introduces a more flexible shape as shown in Figure 2.3 in the form of a kinked triangle.

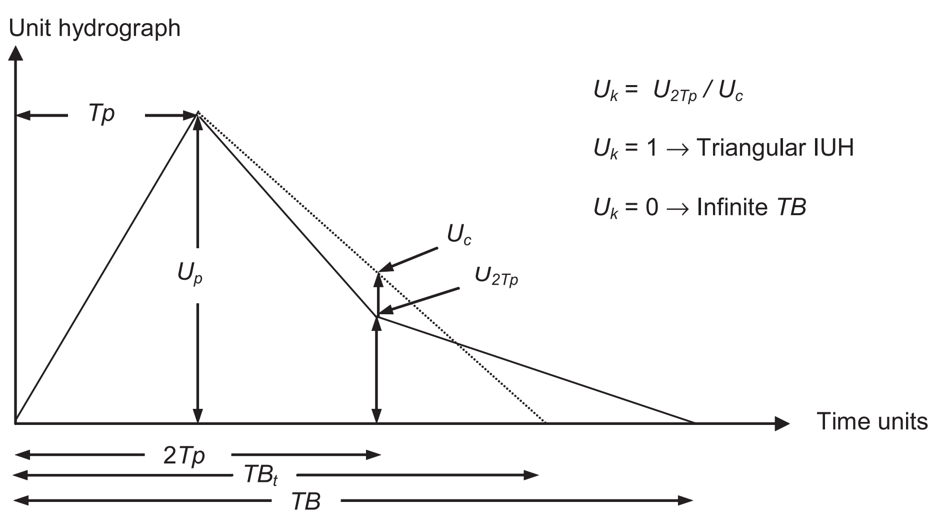


Figure 2.3 *Shape of standard instantaneous unit hydrograph adopted in ReFH*

The kinked triangle is described by a time scaling parameter, Tp, and two dimensionless parameters, U_p and U_k, controlling the height and kink, respectively, of the IUH. The parameter Uk is a multiplier applied to the ordinate Uc of a non-kinked triangular IUH at $2Tp$, i.e.

$$U_c = U_p \frac{TBt - 2Tp}{TBt - Tp} \tag{2.3}$$

where $TB_t = 2\ Tp \,/\, U_p$ to ensure unit-area under the non-kinked triangular unit hydrograph, illustrated by the broken line in Figure 2.3. Thus if $U_k = 1$ the IUH is a simple triangle, but as U_k drops towards zero, the 'lost area' is transferred into the IUH tail by extending the overall time base TB.

$$TB = Tp\left(1 + 2\frac{1 - U_p}{U_k U_c}\right) \tag{2.4}$$

Attempts to relate the parameters controlling the height (U_p) and kink (U_k) of the IUH to readily available catchment descriptors were unsuccessful. Instead, average values of $U_p = 0.65$ and $U_k = 0.8$ are recommended for use in the revitalised FSR/FEH rainfall-runoff method. Because of the kink introduced at $2Tp$ the standard ReFH IUH has a lower peak and a longer time base than the FSR IUH. To convert the dimensionless IUH in Figure 2.3 into the required units of $m^3\ s^{-1}\ mm^{-1}$, a scaling factor of $AREA$ / (3.6 Tp) is applied, where $AREA$ is in km^2 and Tp is in hours.

The IUH can only be used directly when rainfall is given as a continuous function of time. If rainfall is given as a sequence of depths in successive time steps Δt, the IUH must first be converted to an equivalent Δt-hour UH. To transform the IUH in Figure 2.3 into a unit hydrograph of any given time step Δt, the ReFH model uses the S-curve method as described in many standard hydrology textbooks such as Chow *et al.* (1988). The S-curve method replaces the existing FEH approximation of adding half the time step to the time-to-peak of the IUH. This approximation only works if Δt is a small component of Tp and the unit hydrograph is not too skewed.

An S-curve is a summation of the IUH and describes the flow resulting from imposing a continuous uniform-intensity storm on a catchment. The ordinates of the S-curve are denoted by s_t. For an IUH, the S-curve at time t is obtained by integrating the IUH from time zero up to the considered time, i.e.

$$s_t = \int_0^t U(l)dl \tag{2.5}$$

where $U(t)$ are the ordinates of the IUH. Having obtained the S-curve for the IUH, the unit hydrograph for a given time interval Δt is obtained by first offsetting the S-curve by a distance Δt thereby creating a new S-curve, $s_t^{'}$, where

$$s_t^{'} = s_{t-\Delta t} \tag{2.6}$$

The difference between the two S-curves divided by the offset period, Δt, gives the unit hydrograph, $u_t^{'}$ of the desired time period, i.e.

$$u_t^{'} = \frac{1}{\Delta t}\left(s_t - s_{t-\Delta t}\right) \tag{2.7}$$

In practice, this equation is equivalent to defining the unit hydrograph at the n^{th} time step (time $n\ t$) as the volume under the IUH between $t-\Delta t$ and t as seen by combining Equations 2.5 to Equation 2.7:

$$\frac{1}{\Delta t}\left(s_t - s_{t-\Delta t}\right) = \frac{1}{\Delta t}\left[\int_0^t U(l)dl - \int_0^{t-\Delta t} U(l)dl\right] = \frac{1}{\Delta t}\int_{t-\Delta t}^{t} U(l)dl \tag{2.8}$$

Having estimated the Δt-hour UH, the routing of the net rainfall to the catchment outlet is carried out using the convolution equation:

$$q_t = \sum_{i=1}^{t} P_i u_{t-i+1} \qquad \text{for} \qquad t = 1, 2, 3, \ldots \tag{2.9}$$

where q_t denotes the t^{th} ordinate of the rapid response runoff hydrograph, P_i the i^{th} effective rainfall and u_t the t^{th} ordinate of the Δt-hour unit hydrograph.

2.5 Baseflow model

The baseflow model implemented in the ReFH model is based on the linear reservoir concept, with a characteristic recession defined as an exponential decay. The approach, discussed by Appleby (1974) allows the separation of total flow in baseflow and surface flow without knowing the rainfall input. It is based on the contributing area concept, and assumes that the saturated area of the catchment that produces surface runoff is the same area that also produces baseflow recharge, and furthermore that the ratio of recharge to runoff, *BR*, is fixed. An unsaturated area produces neither runoff nor recharge because rainfall is retained as soil moisture. Rainfall that becomes recharge is assumed to pass through a linear storage (with a lag value of *BL*) before emerging into the same channel system that carries the surface runoff. The baseflow hydrograph at the catchment outlet can be determined by routing *BR* times the (as yet undefined) surface flow at the outlet through the groundwater store. The observed hydrograph at the outlet is then the sum of the surface and baseflow hydrographs.

The resulting baseflow model calculates the baseflow at successive time steps Δt apart by linking the baseflow to the observed runoff and the estimated baseflow from the previous time step as

$$z_{t+\Delta t} = k_1 Q_t + k_2 Q_{t+\Delta t} + k_3 z_t \tag{2.10}$$

where Q_t is total observed flow at time t. For the case where the baseflow model is being used to analyse an observed flood event, the constants k_1, k_2 and k_3 are given as

$$k_1 = \frac{BR}{(1+BR)}\left(\frac{BL}{\Delta t}\frac{(1-k_3)}{1+BR} - k_3\right) \tag{2.11}$$

$$k_2 = \frac{BR}{1+BR}\left(1 - \frac{BL}{\Delta t}\frac{(1-k_3)}{1+BR}\right) \tag{2.12}$$

$$k_3 = \exp\left(-\frac{\Delta t}{BL}(1+BR)\right) \tag{2.13}$$

Thus, successive points along the baseflow hydrograph can be determined from the model parameters *BR* and *BL*, a starting baseflow $BF_0 = z_0$ (before the event) and the observed total hydrograph ordinates Q_t during the event.

When the baseflow model is applied to simulate an event, the total flow is not known until after the baseflow has been simulated and added to the direct runoff hydrograph. Therefore, recharge is related directly to the direct runoff in Equation 2.10 and that direct runoff changes q linearly between time steps leading to a baseflow prediction model analogue to Equation 2.10

$$z_{t+\Delta t} = k_1^* q_t + k_2^* q_{t+\Delta t} + k_3^* z_t \tag{2.14}$$

where q is the direct runoff, and the associated parameter values are

$$k_1^* = BR\left(\frac{BL}{\Delta t}\left(1-k_3\right)-k_3\right) \tag{2.15}$$

$$k_2^* = BR\left(1-\left(1-k_3\right)\frac{BL}{\Delta t}\right) \tag{2.16}$$

$$k_3^* = \exp\left(-\frac{\Delta t}{BL}\left(1+BR\right)\right) \tag{2.17}$$

2.6 Application of the ReFH model

Using the ReFH model to model flood events requires the four model parameters (BL, BR, C_{max} and Tp) to be estimated for the particular catchment under consideration. As explained in Chapter 3, the recommended procedure for obtaining the model parameters depends on data availability. If sufficient flood event information is available in the form of coherent sub-daily rainfall and runoff data, then the parameters can be estimated through a joint analysis of these data. This procedure is intensive in both time and data and requires specialised software.

For an ungauged site where no data are available, the ReFH model parameters can be estimated directly from catchment descriptors, which are readily available via the FEH CD-ROM. In the case of an ungauged site, but where ReFH model parameters are available from an event analysis at a nearby similar catchment, data transfer might be the preferred option. An in-depth description of each of the three methods is provided in Chapter 3.

Chapter 3 ReFH model parameter estimation

3.1 Introduction

When using the ReFH model to simulate a flood event on a particular catchment, be it an observed event or a design flood event, it is necessary first to obtain estimates of the four model parameters C_{max}, Tp, BL and BR. The three methods for estimating the model parameters depend on the data availability and are:

- The gauged site: estimate model parameters directly from analysis of observed data;
- The ungauged site: estimate model parameters from catchment descriptorse ; and
- The ungauged site: estimate model parameters using catchment descriptors combined with transfer of information from nearby gauged donor site, i.e. a combination of the two first methods.

Figure 3.1 summarises the decision process and the following three sections set out the methods for each of the three cases.

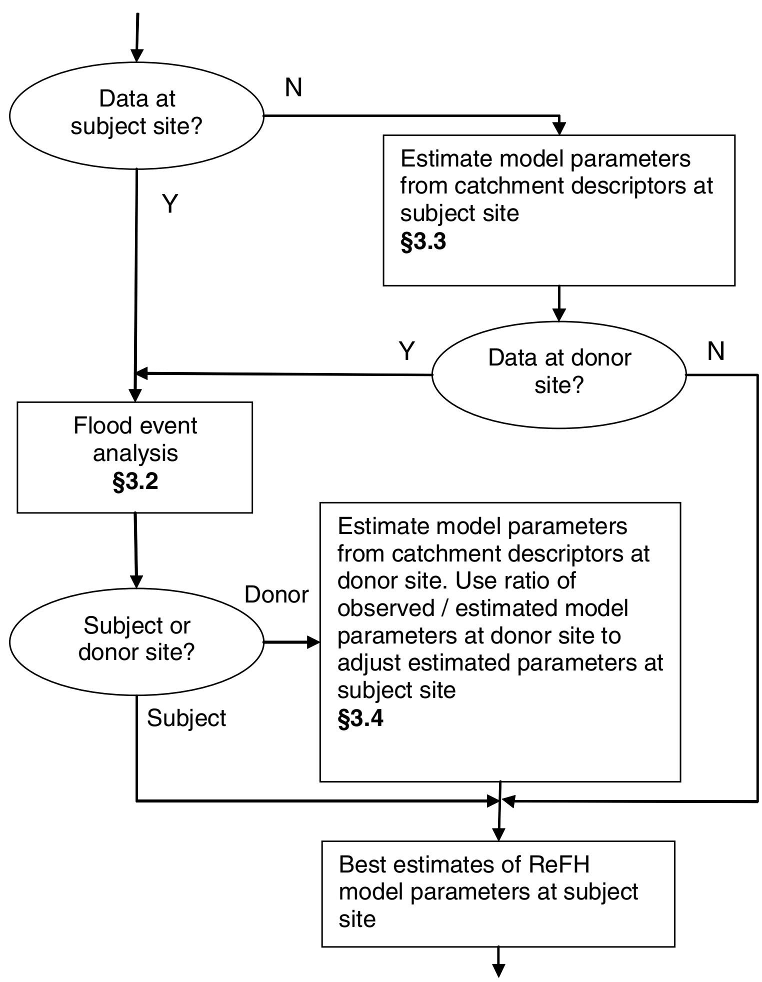


***Figure 3.1** Estimation of the ReFH model parameters*

3.2 The gauged site

Estimation of the ReFH model parameters from observed flood events requires the selection of flood events (§3.2.1), which in turn requires the collection and archiving of hydrometric data from various sources and the processing of these data (§3.2.2) before the parameter estimation can begin. The estimation procedure described here is computationally relatively intensive and will in most cases require access to appropriate software. The ReFH calibration procedure consists of two stages. First, the baseflow parameters *BL* and *BR* are estimated by fitting the baseflow model (§2.5) to the recession part of the observed hydrographs (§3.2.3). Having fitted the baseflow model, the second stage involves a multivariate optimisation procedure for estimating the loss model and routing model parameters, C_{max} and *Tp*, by considering simultaneously the goodness-of-fit over multiple observed flood events (§3.2.4). For each of the observed flood events it is important to get a good estimate of the soil moisture content (C_{ini}) at the start of the event, which is obtained through a soil moisture accounting model driven by daily climatic data for a period of up to two years preceding each event (§3.2.5). An example of estimating of the ReFH parameter at gauged sites is provided in §6.3.

3.2.1 Event selection and data requirements

In practice, the ReFH model parameters can be estimated from a single observed flood event. However, in the development of the ReFH method, catchments were only included where a minimum of five observed events were available and at least one of these events had a peak flow in excess of the median annual maximum flood (QMED). In general, the more events available for the analysis, the less uncertain the resulting estimates of the model parameters will be. Events can be selected from daily rainfall records, and from water level or flow records, simply by identifying days on which the rainfall, water level or flow were particularly high.

For estimation of the four ReFH model parameters from observed flood events, it is necessary to collect and store different sets of hydrometric data, both at a subdaily (hourly) and daily intervals. The data requirements for each individual event are summarised in Table 3.1

Table 3.1 *Hydrometric data requirement for estimating ReFH model parameters from each observed flood event*

Data type	Time step	Description
Rainfall	Average Δt	Catchment average event rainfall, including data from start of water day (09:00am GMT) to start of event to estimate initial soil moisture content, C_{ini}.
Rainfall	Daily	Catchment average rainfall from a period of up to two years leading up to the day of the start of the selected event, enabling estimation of initial soil moisture content, C_{ini}.
Runoff	Instantaneous Δt	Event runoff data, including a sufficiently long period from before and after the actual event to enable estimation of initial baseflow and initial soil moisture content, C_{ini}.
Evaporation	Daily	Potential evaporation from a period of up to two years leading up to the day of the start of the selected event, enabling estimation initial soil moisture content, C_{ini}.

Figure 3.2 shows the definition of observed rainfall. The data requirements for analysis of the event using the ReFH model are indicated. Note that in the ReFH model it is conventional to

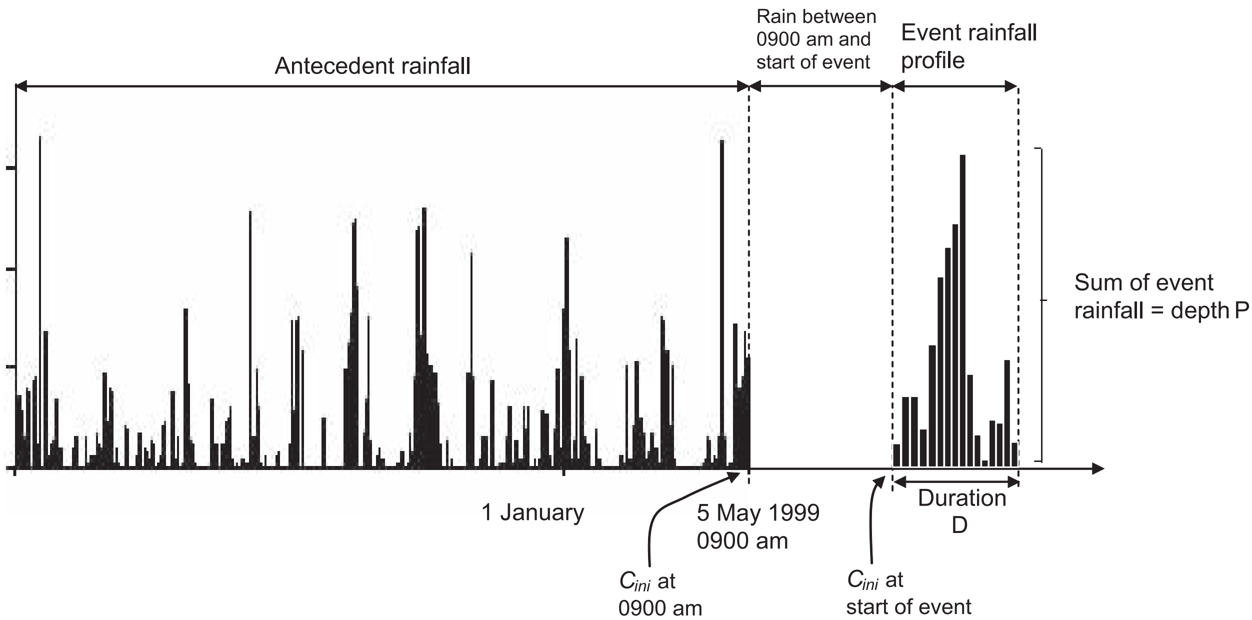


Figure 3.2 *Definition of rainfall event inputs*

store rainfall data against the beginning of the time step under consideration, e.g. the rainfall falling in the hour between 10:00 and 11:00 will be stored at 10:00.

3.2.2 Data requirements

In general, most of the collected hydrometric data must undergo some appraisal and processing before the flood event analysis can proceed. In addition to catchment average rainfall data and gauged flow data for the event itself, information about catchment average values of antecedent rainfall and antecedent potential evaporation are required. As noted by Houghton-Carr (1999), it is vital to make visual inspections of the various data types plotted together to identify potential data problems that may lead to rejection of an event.

Flow data

Flow data recorded at regular intervals are required for a time period covering the entire flood event, including sufficient periods before and after the event to fully capture the rising limb and to enable modelling of the baseflow recession. The chosen time step, Δt, should be selected according to the nature of the catchment response, typically between 15 minutes and 1 hour. Note that only hourly data were used in the development of the ReFH method. Information about the location of flow gauging stations within the UK can be found in the Hydrometric Register and Statistics (CEH/BGS, 2003). The latest information about the range of data and dissemination services is available through the National Water Archive website (*www.ceh.ac.uk/data/nwa.htm*). Alternatively, information on the location of around 1000 gauging stations included in the HiFlows-UK database can be obtained from the Environment Agency (*www.environment-agency.gov.uk/hiflowsuk/*).

Flow data are often obtained from the measuring authority in the form of stage data, which must be converted to flow using a rating equation. There might be doubts about the validity of the flow records, particularly for flood events. For example, the rating may be highly dubious above a certain water level, or the flow record may be artificially influenced. It is important to confirm the accuracy of the rating curve and flow data through discussion with the measuring authority. In addition, the HiFlows-UK database contains information relating to the quality of the flow data at individual gauging stations. This information is indicative and is intended to assist hydrologists to make their own decisions with regard to the suitability of data for analysis.

Catchment average event and antecedent rainfall

The derivation of catchment average rainfall data used in the ReFH model, for the period leading up to the flood event and for the duration of the event itself, is identical to that required by the FSR/FEH method. The following summary is attributed to Houghton-Carr (1999).

Specification of the event rainfall and antecedent rainfall, and identification of any rain that falls between 09:00 on the first day of the event and the actual start of the event, is ideally accomplished by deriving the catchment average rainfall for the event. Distinguishing between event and antecedent rainfall is best achieved by plotting the rainfall and flow together, whereby it is usually possible to infer the bursts of rainfall that were directly responsible for the event. However, a certain amount of judgement may have to be applied, for example in deciding whether to divide a multi-burst storm into antecedent rainfall (contributing to the initial soil moisture content) and event rainfall (contributing directly to the flood event).

Traditional procedures for deriving catchment average rainfall, such as used in both FSR (NERC, 1975) and FSSR16 (Institute of Hydrology, 1985), require at least one recording raingauge, ideally located towards the centre of the catchment, and several daily raingauges evenly distributed within, or close to, the catchment. Radar-derived rainfall data can provide a valuable additional source of information, when used in conjunction with measurements from at least one conventional raingauge (Wood *et al.*, 2000). There are many acceptable methods for deriving areal rainfall ranging in sophistication and descriptions of these methods can be found in standard hydrology textbooks such as Chow *et al.* (1988), Wilson (1990) and Shaw (1994). A comprehensive review of methods for obtaining catchment average rainfall can be found in Jones (1983).

Catchment average potential evaporation

When modelling the antecedent soil moisture content, it is necessary to have estimates of daily potential evaporation, E_p, defined as the volume of water evaporated from an idealised extensive free water surface under existing atmospheric conditions. Time series of daily potential evaporation can either be obtained directly from measurements of E_p or calculated using a model linking the evaporation rate to other climatic variables. Numerous models for estimating evaporation are available and described in standard hydrological textbooks such as Chow *et al.* (1988), Bras (1990), Wilson (1990), Shuttleworth (1993) and Shaw (1994).

The methods range from advanced data-extensive research models, based on complex descriptions of energy budgeting and water movements in the soil-vegetation-atmosphere interface (Shuttleworth, 1993), to more empirical methods. The choice of method is very much a matter of balancing the need for accuracy with data availability. In the development of the revitalised FSR/FEH method, six-parameter sinusoidal functions were fitted to average monthly potential evaporation as estimated for 40×40 km grid squares from the UK Met Office MORECS system. A simpler and more generic approach can be used where daily potential evaporation at the n^{th} day of the year is estimated as

$$E_p(n) = \alpha\left(1 + \sin\left(2\pi\frac{(n-90)}{365}\right)\right) \tag{3.1}$$

where $n = 1$ corresponds to 1st January and α is the average daily potential evaporation.

3.2.3 Baseflow parameters

The method for estimating the two ReFH baseflow model parameters *BL* and *BR* is based on analysis of hydrograph recessions for individual events. The final estimate for a specific catchment is then taken as the average of the results obtained for the individual events. Estimates of *BL* can be determined from the available recession beyond the point chosen as 'end of direct runoff' using hydrological judgement, as shown in Figure 3.3.

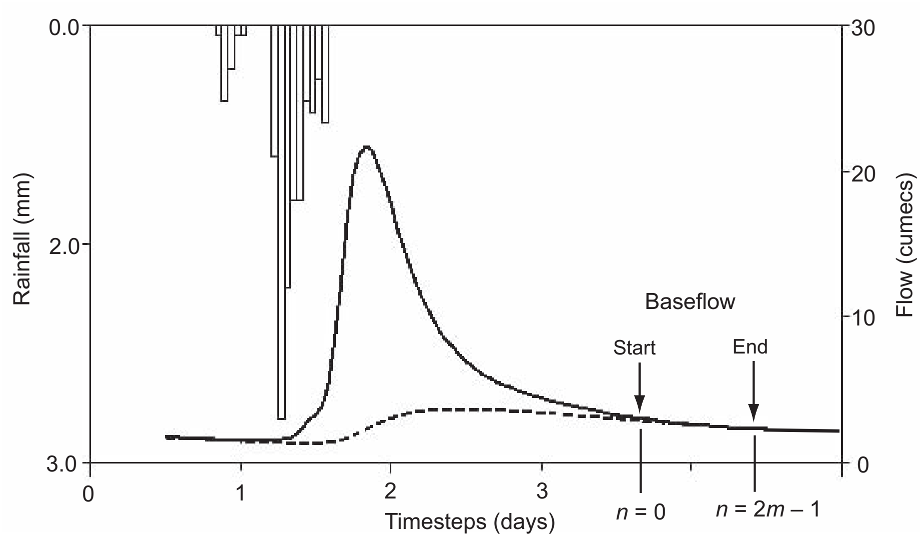


***Figure 3.3** Selection of points for baseflow estimation*

Baseflow is modelled as a linear reservoir, which result in a recession that decays linearly with a recession constant *BL*, i.e.

$$Q_t = Q_0 \exp\left(-\frac{1}{BL}\,t\right) \tag{3.2}$$

where Q_0 is the flow at the end of direct runoff. From Equation 3.2 flow can be written in terms of the number of flow ordinates, *n*, into the recession

$$Q_t = Q_0\left(\exp\left(-\frac{1}{BL}\,\Delta t\right)\right)^n = Q_0\,K^n \quad , \qquad n = 0, 1, 2 \ldots 2m\text{–}1 \tag{3.3}$$

where Δt is the time step of the flow ordinates and *m* is an even number and

.

$$K = \exp\left(-\frac{1}{BL}\,\Delta t\right) \tag{3.4}$$

To ensure that the estimation of the recession constant is not unduly influenced by local particularities in the flow data of the recession curve, *BL* is estimated by considering the flow averaged over several time steps rather than individual flow values. The interval between the two points defining the start ($n = 0$) and end ($n = 2m$–1) of baseflow is divided into two sections ignoring any remaining odd values. To derive an estimator for *BL* the model flow values for each section, as given by Equation 3.3, are added together as

$$V_1 = \sum_{i=0}^{m-1} Q_0 \left(\exp(-BL\Delta t)\right)^i = Q_0 \sum_{i=0}^{m-1} K^i$$
$$V_2 = \sum_{i=m}^{2m-1} Q_0 \left(\exp(-BL\Delta t)\right)^i = Q_0 K^m \sum_{i=0}^{m-1} K^i \tag{3.5}$$

and BL can then be estimated by taking the natural logarithm of the ratio of the two sums, i.e.

$$BL = -\left(\frac{\ln(V_2) - \ln(V_1)}{m\Delta t}\right)^{-1} \tag{3.6}$$

where $\Delta t = 1$ hour for hourly data. In practice, V_1 and V_2 are estimated by adding together the observed flow ordinates in the two sections.

In the ReFH analysis, the corresponding estimate of BR was derived by optimisation on a trial and error basis until the derived baseflow hydrograph formed a close match to the same part of the recession. This optimisation was performed using a simple linear search procedure, minimising the weighted mean square error between the observed and predicted baseflow values (using a weighting factor of 2 whenever modelled baseflow exceeds the observed value) as

$$\min_{BR} \left\{ \sum_{t=t_0}^{t_e} \left[\left(z_t(BL, BR) - Q_{t,obs} \right) \gamma \right]^2 \right\}, \qquad \gamma = \begin{cases} 1 & z_t \le Q_{t,obs} \\ 2 & z_t > Q_{t,obs} \end{cases} \tag{3.7}$$

where t_0 and t_e are the chosen start and finish of the baseflow recession part of the event hydrograph. The estimation through an optimisation procedure renders the baseflow estimation procedure unsuitable for manual use and necessitates the use of appropriate software tools. If the hydrograph recession is not long enough to make meaningful inference about the baseflow parameter, the particular event should be removed from the analysis.

It should be noted that the estimation of the baseflow model for each event is identical to separating the baseflow and the direct runoff hydrographs. As described by Pilgrim and Cordery (1993), baseflow separation techniques are often developed into simple techniques matching the analytical procedures at hand, rather than being based on modelling physical processes.

3.2.4 Estimation of C_{max} and Tp

The loss model and routing model parameters (C_{max}, Tp) can be estimated simultaneously by finding the set of parameters resulting in the optimal performance in terms of reproducing the observed flows in a series of different flood events. The optimisation scheme is illustrated in Figure 3.4 and allows the two parameters to be estimated from one or several events simultaneously by minimising an objective function defined as the squared difference between observed and simulated runoff, i.e. the mean square error

$$MSE = \frac{1}{M} \sum_{m=1}^{M} \sum_{t=1}^{N_m} \left(Qsim_{t,m} - Qobs_{t,m} \right)^2 \tag{3.8}$$

where M is the number of flood events under consideration and N_m is the number of time steps in the m^{th} flood event. To prevent unrealistic values of C_{max} being estimated, it is generally recommended that C_{max} should be modelled as a product of the field capacity, FC, and a dimensionless scaling factor, SM', as

$$C_{max} = 2FC\,SM' \tag{3.9}$$

where the field capacity is expressed in mm and is obtained using an empirical relationship

$$FC = 49.9\ PROPWET^{-0.51}\ BFIHOST^{0.23} \tag{3.10}$$

Combining Equations 3.9 and 3.10, it is possible to perform the optimisation using *SM'* and *Tp*. The use of *SM'* rather than C_{max} was found to give more stable solutions to Equation 3.8.

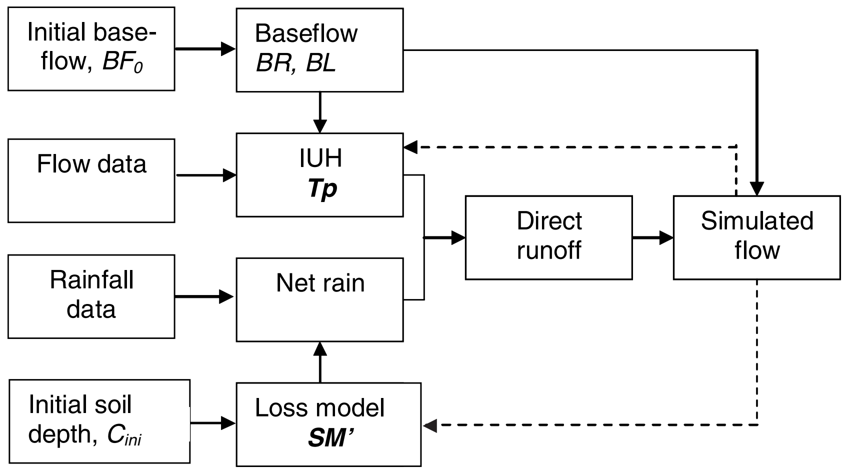


Figure 3.4 *Multivariate optimisation scheme for joint estimation of C_{max} (SM') and Tp. Parameters in **bold** are used by the optimisation procedure.*

For each event the optimisation routine requires information concerning the initial baseflow value (BF_0) and the initial soil moisture content (C_{ini}) in order to simulate the flow response to the observed hyetograph. The initial baseflow value is defined as the flow in the river just before the start of the event. The procedure for estimating C_{ini} is more complex and described in §3.2.5.

3.2.5 Antecedent rainfall and soil moisture

Use of the loss model in Equation 2.1 requires an estimate of the soil moisture content, C_{ini}, at the beginning of the selected flood event. When analysing observed flood events using the ReFH model, an estimate of C_{ini} is obtained for each individual event through modelling of the antecedent soil moisture content using a separate daily soil moisture accounting model driven by continuous daily records of rainfall and evaporation as

$$\frac{dm}{dt} = f_t - d_t - E_t \tag{3.11}$$

where m_t is soil moisture content, f_t is infiltration, d_t is drainage out of the soils and E_t is evaporation. To model evaporation and drainage, two threshold values, field capacity (*FC*) and rooting depth (*RD*), have been introduced as illustrated in Figure 3.5.

The location of the rooting depth is fixed at a ratio of $RD/FC = 0.3$ for every catchment, thereby reducing the number of parameters to be estimated. The infiltration, *f*, is modelled using a uniform PDM model and given as

$$f_t = \frac{P_t}{\Delta t}\left(1 - \frac{m_t}{SM}\right)^{\frac{1}{2}} \tag{3.12}$$

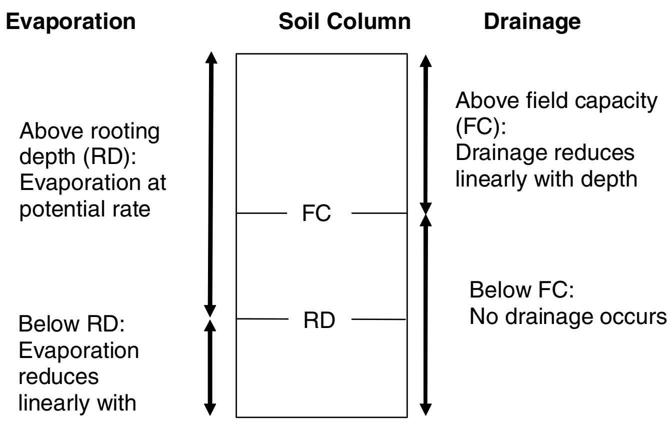


Figure 3.5 *Antecedent soil moisture accounting model*

as described in Appendix A, Equation A.8, where SM is defined as the catchment average soil moisture capacity and Δt is 1 day. Drainage out of the soil occurs once the soil moisture content exceeds the field capacity ($m_t > FC$) and is modelled using a drainage coefficient k, as

$$d_t = k\,(m_t - FC) \tag{3.13}$$

When Equation 3.11 is solved over a time step of a day (Δt = 1 day), the drainage rate ψ is expressed as a daily decay rate (DK) where $DK = \exp(-k\,\Delta t)$. In the ReFH model, a constant value of $DK = \exp(-k\,\Delta t) = 0.8$ for the daily decay rate has been applied.

As long as the soil moisture content m_t exceeds the rooting depth ($m_t > RD$), the evaporation is assumed to be at potential rate ($E_t = E_p$). When the soil moisture content falls below rooting depth ($m_t < RD$), actual evaporation reduces linearly as

$$E_t = \frac{m_t}{RD} E_p \tag{3.14}$$

The numerical solution of Equation 3.11 is derived through a finite difference scheme as shown in Appendix B. To get the antecedent soil moisture content at the onset of the event, the soil moisture accounting model in Equation 3.11 is used to model the continuous soil moisture for a continuous period, assuming soil moisture at field capacity on 1 January the

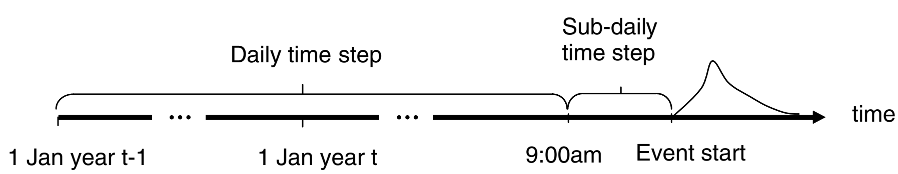


Figure 3.6 *Time scale for modelling of antecedent soil moisture*

year before the year in which the event occurred (see Figure 3.6). The soil moisture accounting model is run at a daily time step up to 09:00 am on the day of the event.

Finally, the development of the soil moisture content between 09:00 am and the start of the actual flood event is modelled by solving Equation 3.11 for a single time step. Alternatively, Equation 3.11 can be solved for each hour between 09:00 am and the start of the event, although this was not done in the development of the methodology.

When converting the actual soil moisture volume, m, derived by the antecedent model into an equivalent soil moisture content for the PDM loss model in Equation 2.1, C_{ini}, the relationship derived in Appendix A, Equation A.8 is rearranged to obtain

$$C_{ini} = C_{\max}\left[1-\left(1-\frac{m_{ini}}{SM}\right)^{\frac{1}{2}}\right] \tag{3.15}$$

where m_{ini} is the soil moisture volume of the daily accounting model at the beginning of the flood event.

Estimation of the ReFH parameters through analysis of observed data is strongly recommended whenever possible. The computational procedures are probably too intensive to be carried out manually and it is generally recommended that specialised software should be used. A full example showing the estimation of the model parameters from analysis of observed flood events is given later in §6.3.

3.3 The ungauged site

To enable the ReFH rainfall-runoff model parameters to be estimated for catchments where no hydrometric data are available, a set of multivariate regression relationships between model parameters and catchment descriptors has been developed. The catchment descriptors are generally available from the FEH CD-ROM for any catchment in the UK larger than 0.5 km^2 (Bayliss, 1999). Estimates of the ReFH model parameters made using the regression relationships are accompanied by relatively large uncertainties, resulting from both limited data and the imperfection of the regression models. It is therefore recommended that the regression equations should never be the considered the preferred option. If additional information from relevant gauged sites exists.

Consider the assumed log-linear relationship between a model parameter y and a set of P different catchment characteristics x_k given as

$$\ln[y] = \ln[b_0] + b_1 \ln[x_1] + b_2 \ln[x_2] + \ldots \tag{3.16}$$

which, on exponentiation, yields

$$y = b_0\, x_1^{\,b_1} x_2^{\,b_2} \ldots$$

where

y_i = ReFH model parameter
b_k = regression model parameter, $k = 0, \ldots, P$
x_k = catchment descriptor $k = 1, \ldots, P$

Use of the natural logarithm in Equation 3.16 on an independent variable which can take zero as a value is not possible: thus *URBEXT* is replaced by 1+*URBEXT*. The regression model parameters are estimated using a weighted least squares (WLS) procedure, which is similar to ordinary least squares (OLS) except that observations are weighted to allow for differences in variance (Robson and Reed, 1999). Here, as in Marshall (2000), the weight for the i^{th} catchment, w_i, is defined as the square root of the number of events available at that particular site, i.e.

$$w_i = \sqrt{n_i} \tag{3.17}$$

where n_i is the number of events analysed at each site. In practice, the WLS is equivalent to OLS where the weights have been applied to the dependent and explanatory variables. From applying the ReFH model to each of the 101 gauged catchments and 1265 events, coherent sets of the four ReFH parameters were estimated. The full list of catchments and their optimised parameter values are shown in Appendix C. For each catchment descriptor equation, the goodness-of-fit measures r^2 and *fse* are reported as well as the number of catchments included in the estimation of the equation.

3.3.1 Loss model

The loss model parameter C_{max} is estimated based on the baseflow index *BFIHOST* and *PROPWET* as

$$C_{\max} = 596.7\, BFIHOST^{0.95}\, PROPWET^{-0.24}$$
$$r^2 = 0.55,\quad fse = 1.61,\quad n = 101 \qquad (3.18)$$

The range of the catchment descriptor values used for estimation of Equation 3.18 are shown in Table 3.2.

***Table 3.2** The range, mean and 25- and 75-percentiles for variables in the C_{max} catchment descriptor equation*

	Min	25%	Median	75%	Max
C_{max}	149	250	321	411	796
BFIHOST	0.178	0.365	0.436	0.524	0.658
PROPWET	0.25	0.32	0.39	0.53	0.71

3.3.2 Routing model

The routing model parameter is the time-to-peak (*Tp*) of the instantaneous unit hydrograph. The optimal combination of catchment descriptors was found to be equal to the combination adopted by Houghton-Carr (1999) for predicting time-to-peak in the FEH methodology. The resulting equation for *Tp* in the ReFH model is

$$Tp = 1.56\, PROPWET^{-1.09}\, DPLBAR^{0.60} \left(1 + URBEXT_{1990}\right)^{-3.34} DPSBAR^{-0.28}$$
$$r^2 = 0.81,\quad fse = 1.31,\quad n = 101 \qquad (3.19)$$

The ranges of the catchment descriptor values used for estimation of Equation 3.19 are shown in Table 3.3

***Table 3.3** The range, mean and 25- and 75-percentiles for variables in the Tp catchment descriptor equation*

	Min	25%	Median	75%	Max
Tp	1.32	3.61	5.59	8.25	24.70
PROPWET	0.25	0.32	0.39	0.53	0.71
DPLBAR	2.2	9.4	14.2	19.6	37.5
$URBEXT_{1990}$	0.000	0.001	0.009	0.035	0.433
DPSBAR	11.61	34.90	74.68	124.65	215.66

3.3.3 Baseflow model

A regression model has been developed for each of the two baseflow model parameters *BL* and *BR*. Of the four ReFH model parameters, the two baseflow models show the least relationship with the available catchment descriptors.

The final model for baseflow lag, BL, is:

$$BL = 25.5\, BFIHOST^{0.47}\, DPLBAR^{0.21}\, PROPWET^{-0.53} \left(1 + URBEXT_{1990}\right)^{-3.01}$$
$$r^2 = 0.41, \quad fse = 2.03, \quad n = 100 \tag{3.20}$$

The ranges of the catchment descriptor values used for estimation of Equation 3.20 are shown in Table 3.4.

Table 3.4 *The ranges, mean and 25- and 75-percentiles for variables in the BL catchment descriptor equation*

	Min	25%	Median	75%	Max
BL	13.04	29.14	43.80	62.90	109.68
BFIHOST	0.178	0.365	0.436	0.524	0.779
DPLBAR	2.17	9.38	14.11	19.68	37.53
PROPWET	0.25	0.32	0.39	0.53	0.71
$URBEXT_{1990}$	0.000	0.001	0.010	0.036	0.433

The equation for Baseflow recharge, BR, is:

$$BR = 3.75\, BFIHOST^{1.08}\, PROPWET^{0.36}$$
$$r^2 = 0.34, \quad fse = 2.04, \quad n = 100 \tag{3.21}$$

The ranges of the catchment descriptor values used for estimation of Equation 3.21 are shown in Table 3.5.

Table 3.5 *The ranges, mean and 25- and 75-percentiles for variables in the BR catchment descriptor equation*

	Min	25%	Median	75%	Max
BR	0.41	0.84	1.07	1.50	3.29
BFIHOST	0.178	0.365	0.436	0.524	0.779
PROPWET	0.25	0.32	0.39	0.53	0.71

A worked example showing the procedure is shown in Example 3.1.

3.4 Information transfer from donor sites

In the case where no information is available at the site of interest, the ReFH model parameters estimated using catchment descriptors can, in some cases, be enhanced through transfer of information from one or more nearby gauged catchments. In line with the terminology of the FEH, such catchments are referred to as donor catchments, and the information they provide is referred to as local data. Once a suitable donor site has been identified for the information transfer, each individual ReFH model parameter Y at the site of interest is estimated as

$$Y_{s,adj} = Y_{s,cds} \frac{Y_{g,obs}}{Y_{g,cds}} \tag{3.22}$$

where subscripts s and g refer to the ungauged subject site and the gauged donor site, respectively, and the subscripts *cds*, *obs* and *adj* refer to the catchment descriptor estimate at the gauged and

Example 3.1
Estimation of ReFH model parameters from catchment descriptors

Catchment: Leven at Leven Bridge (25005) (IHDTM grid. ref. 444500 512100)

Relevant catchment descriptors from FEH CD-ROM v1.0:
BFIHOST = 0.381, *PROPWET* = 0.34, *DPLBAR* = 25.49 km,
DPSBAR = 74.50 m km^{-1}, $URBEXT_{1990}$ = 0.010

Maximum soil moisture depth (C_{max})

$C_{max} = 596.7\ BFIHOST^{0.95}\ PROPWET^{-0.24}$
$= 596.7\ (0.381)^{0.95}\ (0.34)^{-0.24}$ = 309 mm

Time to peak (*Tp*)

$Tp = 1.56\ PROPWET^{-1.09}\ DPLBAR^{0.60}\ (1 + URBEXT_{1990})^{-3.34}\ DPSBAR^{-0.28}$
$= 1.56\ (0.34)^{-1.09}\ (25.49)^{0.60}\ (1 + 0.010)^{-3.34}\ (74.50)^{-0.28}$ = 10.21 hours

Baseflow lag (*BL*)

$BL = 25.5\ BFIHOST^{0.47}\ DPLBAR^{0.21}\ PROPWET^{-0.53}\ (1 + URBEXT_{1990})^{-3.01}$
$= 25.5\ (0.381)^{0.47}\ (25.49)^{0.21}\ (0.34)^{-0.53}\ (1 + 0.010)^{-3.01}$ = 55.0 hours

Baseflow recharge (*BR*)

$BR = 3.75\ BFIHOST^{1.08}\ PROPWET^{0.36}$
$= 3.75\ (0.381)^{1.08}\ (0.34)^{0.36}$ = 0.90

subject sites, the observed value obtained through analysis of observed events at the gauged site and the adjusted value at the subject site, respectively. For the case where more than one useful donor site exists, Houghton-Carr (1999) introduced a more complicated adjustment procedure where each donor is weighted according to how relatively similar to the subject site it is perceived to be. Consider a case where M suitable donors have been identified, then the final adjusted estimate is obtained as

$$Y_{s,adj} = Y_{s,cds} \frac{\sum_{i=1}^{M} w_i\, Y_{i,obs} / Y_{i,cds}}{\sum_{i=1}^{M} w_i} \tag{3.23}$$

where w_i is the weight assigned to each donor site.

No authoritative set of rules exists for choosing suitable donor sites. General caution is advised when estimating the ReFH model parameters using information transfer. Houghton-Carr (1999) provided a set of principles guiding the selection of donor sites for estimating model parameters in the FSR/FEH rainfall-runoff method, but stressed that they were, indeed, guidance rather than definitive principles. These rules are repeated below:

- The catchment descriptors should be comparable; in particular catchment area should differ by less than a factor of 5.

- The catchment centroids should normally be separated by a distance of less than 50 km. The requirement for the catchments to be physically close arises because estimation errors in generalisation methods are not entirely random but tend to be spatially clustered, i.e. they have a tendency to overestimate or underestimate flood potential in particular localities.
- The catchments should be substantially rural. This is a stringent criterion, with the purpose of discouraging transfer of information between mainly rural and substantially urban catchments. In the event that both the subject site and the gauged site are moderately or heavily urbanised, it is important to verify that the location and concentration of the urban area, and the underlying soil types, are broadly comparable. These subcriteria reflect the dominant influence of urbanisation on flood potential, and the fact that urban effects are complex and not fully indexed by the urban extent.
- Transfer of information between catchments within the same river basin is preferred, the ideal case being when the gauged site is located just upstream or downstream of the subject site. However, transfer from an otherwise suitable catchment in a neighbouring or nearby river basin is also useful.

An example of using a donor site to enhance the estimation of the ReFH model parameter at an ungauged site is provided in Example 3.2.

Example 3.2
Estimation of the ReFH model parameters through information transfer

Catchments:
Subject: Leven at Leven Bridge (IHDTM grid. ref. 444500 512100)
Donor: Greta at Rutherford Bridge (25006) (IHDTM grid. ref. 403250 512250)

Relevant catchment descriptors (subject catchment) from FEH CD-ROM v1.0:
BFIHOST = 0.381, *PROPWET* = 0.34, *DPLBAR* = 25.49 km,
DPSBAR = 74.50 m km^{-1}, $URBEXT_{1990}$ = 0.010

Relevant catchment descriptors (donor catchment) from FEH CD-ROM v1.0:
BFIHOST = 0.242, *PROPWET* = 0.62, *DPLBAR* = 12.39 km,
DPSBAR = 66.40 m km^{-1}, $URBEXT_{1990}$ = 0.001

For the subject catchment, the ReFH model parameters have been estimated using catchment descriptors in Example Box 3.1

$C_{max,\mathrm{s,cds}}$ = 309 mm, $Tp_{\mathrm{s,cds}}$ = 10.21 hours, $BL_{\mathrm{s,cds}}$ = 55.0 hours and $BR_{\mathrm{s,cds}}$ = 0.90

For the gauged donor catchment (25006), the ReFH model parameters derived from catchment descriptors are

$C_{max,\mathrm{g,cds}}$ = 174 mm, $Tp_{\mathrm{g,cds}}$ = 3.66 hours, $BL_{\mathrm{g,cds}}$ = 28.5 and $BR_{\mathrm{g,cds}}$ = 0.68

The corresponding parameter estimates at the donor sites obtained through analysis of observed events can be found in Appendix C of this report

$C_{max,\mathrm{g,obs}}$ = 190 mm, $Tp_{\mathrm{g,obs}}$ = 2.79 hours, $BL_{\mathrm{g,obs}}$ = 34.1 and $BR_{\mathrm{g,obs}}$ = 0.62

Through the use of Equation 3.22, a donor correction factor and the corresponding adjusted parameter value for the subject catchment can be derived:

Maximum soil moisture depth (C_{max})
$C_{max,\mathrm{s,adj}} = C_{max,\mathrm{s,cds}}\ (C_{max,\mathrm{g,obs}}\ /\ C_{max,\mathrm{g,cdf}})$
$= 309\ (174\ /\ 190) = 309\ (1.09)$ = 338 mm

Time to peak (Tp)
$Tp_{\mathrm{s,adj}} = Tp_{\mathrm{s,cds}}\ (Tp_{\mathrm{g,obs}}\ /\ Tp_{\mathrm{g,cdf}})$
$= 10.21\ (2.79\ /\ 3.66) = 10.21\ (0.76)$ = 7.78 hours

Baseflow lag (BL)
$BL_{\mathrm{s,adj}} = BL_{\mathrm{s,cds}}\ (BL_{\mathrm{g,obs}}\ /\ BL_{\mathrm{g,cdf}})$
$= 55.0\ (34.1\ /\ 28.4) = 55.0\ (1.20)$ = 65.7 hours

Baseflow recharge (BR)
$BR_{\mathrm{s,adj}} = BR_{\mathrm{s,cds}}\ (BR_{\mathrm{g,obs}}\ /\ BR_{\mathrm{g,cdf}})$
$= 0.90\ (0.62\ /\ 0.68) = 0.90\ (0.91)$ = 0.82

Chapter 4 Design flood estimation

4.1 Introduction

This chapter outlines the development of the revitalised FSR/FEH design event model, which is based on the ReFH rainfall-runoff model, and describes how it can be applied in hydrological design studies. In this context it is important to distinguish between the simulation of an observed flood event on a given catchment and the estimation of a design flood hydrograph. The latter is based on a design model constructed to yield the hydrograph of a specified return period when the input variables (design storm and initial values of soil moisture content and baseflow) have been specified accordingly. The design storm inputs are probabilistic estimates with an associated return period and the initial conditions are selected using the physical attributes of the catchment such as area, soil properties, general wetness and degree of urbanisation. As well as providing design hydrographs, the design model can be used to produce a flood frequency curve for a given catchment by plotting the peak flow of the T-year event against frequency for a range of return periods.

The ReFH design event model was developed and calibrated to ensure that the design hydrograph of a specified return period is generated from a unique set of design input variables (rainfall depth, duration, profile and initial soil moisture content). The calibration was based on the 100 catchments for which both ReFH model parameters and annual maximum series of peak flow were available. Further details of the calibration of the design model are given in Appendix D.

In §4.2, the structure of the ReFH design event model is introduced and rules for choosing the design storm, soil moisture and baseflow parameters are considered in detail in §4.3 to §4.7. Worked examples of the use of the ReFH design event model are given in Chapter 6.

4.2 The ReFH design flood simulation package

The revitalised FSR/FEH rainfall-runoff design model is based on the ReFH model as shown in Figure 4.1.

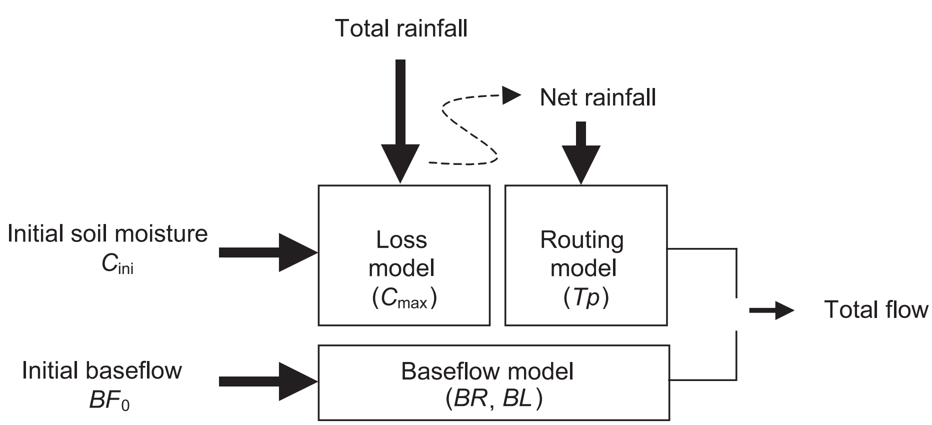


Figure 4.1 *Schematic representation of the ReFH design model*

Implementation of the ReFH model for hydrological design requires particular values of rainfall, initial soil moisture and initial baseflow known as design inputs. A rainfall of a given return period can produce a wide range of estimated design floods, depending on the storm duration, initial catchment wetness and, less critical in most cases, the temporal profile of the storm.

The ReFH design package provides guidance for selecting a single set of design inputs required to simulate a design flood event with a peak flow value of a required return period. Different recommendations for rural and urban catchments are given. Rural catchments are considered more prone to flooding in the winter half of the year with sustained rainfall over a wet catchment; urban catchments are more likely to flood as a result of more intense storms over drier catchments during the summer. The revitalised FSR/FEH rainfall-runoff method has adopted the FSR (Volume II, §3.4) definitions of summer and winter seasons as May-October and November-April. To distinguish between rural and urban catchments, a threshold value of $URBEXT_{1990} = 0.125$ has been adopted in line with the recommendations in the FEH rainfall-runoff method (Houghton-Carr, 1999; §3.2.3). If $URBEXT_{1990} < 0.125$, catchments are considered rural, and subsequently those where $URBEXT_{1990} \geq 0.125$ are considered urban. Figure 4.2 shows the influence of the design inputs with respect to the steps in the calculation of the *T*-year design flood event.

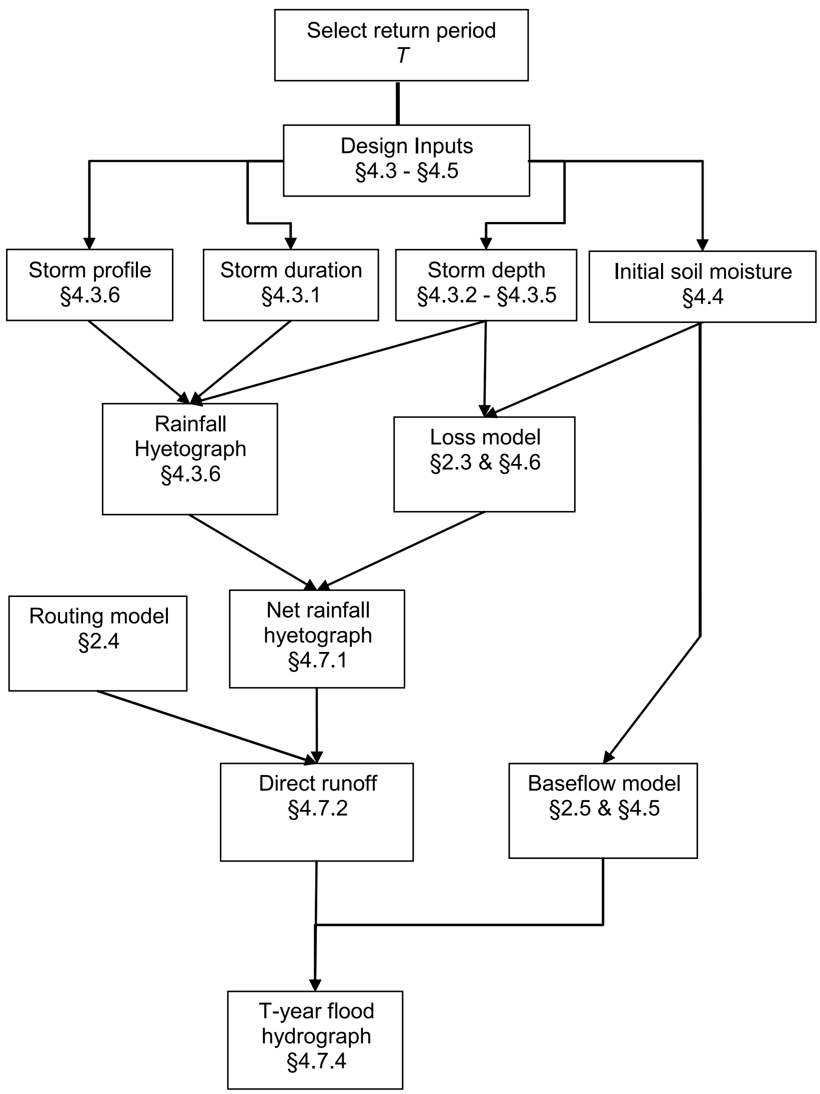


Figure 4.2 *Steps in the calculation of the T-year design flood event*

4.3 Design rainfall inputs

4.3.1 Design storm duration

The method for estimating the duration of a design storm in the ReFH method has been adopted directly from the FSR/FEH method, where the design storm duration (*D*) is based on a formula, which approximates the duration giving the largest flood magnitude (Houghton-Carr, 1999). The design storm duration for a particular catchment depends on the response time of the catchment (time to peak, *Tp*) and the general wetness of the catchment (as measured by the standard average annual rainfall, *SAAR*) as

$$D = Tp\left(1 + \frac{SAAR}{1000}\right) \tag{4.1}$$

For the FSR/FEH method it was found that curves of flood magnitude against storm duration were generally flat, indicating that the method is not overly sensitive to the choice of storm duration (Houghton-Carr, 1999). However, the duration will have an impact on the volume of the generated design flood event, where the longer the design storm the larger the volume of the resulting design flood.

It is important to choose the design storm duration to be an odd integer multiple of the chosen data interval Dt to enable the design storm hyetograph to be derived according to the procedure outlined in the FSR (NERC, 1975).

Example 4.1
Calculation of design storm duration *D*

Catchment: Mellte at Pontfeddfechan (58006) (IHDTM grid ref. 291350 208100)

Relevant catchment descriptors and other information from FEH CD-ROM v1.0:
SAAR = 1981 mm, D*t* = 0.5 hours, *Tp* = 2.26 hours.

The design storm duration *D* is calculated from *Tp* and *SAAR* using Equation 4.1:

D = *Tp* (1 + *SAAR*/1000) = 2.26 (1 + 1981 / 1000)

D = 6.7 hours

In this instance, Dt = 0.5 hours so *D* is rounded down to 6.5 hours, the nearest odd integer multiple of Dt:

D = 6.5 hours

4.3.2 Design rainfall depth

As part of the FEH (Institute of Hydrology, 1999), a spatially generalised depth-duration-frequency (DDF) model was developed, enabling estimation of design rainfall with durations between 30 minutes and 8 days at any site in the UK. The DDF model was developed by analysing annual maximum rainfall data and superseded the results presented in Volume II of the FSR (NERC, 1975) concerning design rainfall, except for estimation of probable maximum precipitation (PMP). The model is implemented on the FEH CD-ROM.

The revitalised rainfall-runoff method introduces a more comprehensive seasonal analysis than currently available in the existing FSR/FEH method and, therefore, it requires estimates of seasonal design rainfall to be available. In the revitalised rainfall-runoff method, the seasonal design rainfall is derived from the FEH DDF model by multiplying FEH estimates of design rainfall with a seasonal correction factor. The seasonal correction factor depends on the *SAAR* of the considered catchment. With the introduction of the seasonal correction factor, the catchment average seasonal design rainfall depth is calculated as

$$P = RDDF \times ARF \times SCF \tag{4.2}$$

where *RDDF* is the point estimate of design rainfall obtained from the FEH DDF model (§4.3.3), *ARF* is the areal reduction factor transforming point rainfall to catchment average rainfall (§4.3.4) and *SCF* is the seasonal correction factor transforming annual maximum rainfall to seasonal maximum rainfall (§4.3.5).

4.3.3 FEH Depth-Duration-Frequency Model

Background and details of the FEH DDF model are presented by Faulkner (1999) and only the main results of importance for its application in design flood estimation are summarised here. The DDF model has six parameters (c, d_1, d_2, d_3, e, f) defining the log-Gumbel relationship between rainfall depth, duration and frequency (return period). The model considers three intervals of duration (D) where the depth (R) is estimated as

For $D \leq 12$ hours

$$\ln[R] = (cy + d_1)\ln[D] + ey + f$$

For $12 < D \leq 48$ hours (4.3)

$$\ln[R] = \ln[R_{12}] + (cy + d_2)(\ln[D] - \ln[12])$$

For $D > 48$ hours

$$\ln[R] = \ln[R_{48}] + (cy + d_3)(\ln[D] - \ln[48])$$

where the units of R and D are mm and hours, respectively, and y is the Gumbel reduced variate given as $y = -\ln[-\ln[1-1/T]]$.

The six parameters (c, d_1, d_2, d_3, e, f) are available on the FEH CD-ROM for all points in a 1 km grid covering the UK. For each catchment on the FEH CD-ROM larger than 0.5 km^2, the catchment average set of parameters have been derived as the weighted average of point values, determined by overlaying the catchment boundary on the 1 km grid squares (Faulkner, 1999). The catchment average DDF model parameters were used in the development of the design model.

4.3.4 Areal Reduction Factors

The estimates of design rainfall calculated using the DDF model are point values as the model is based on data from individual gauges. To allow the estimation of catchment average design rainfall, the concept of the areal reduction factor *ARF* has been adopted from the existing FSR/FEH method. The FSR (NERC, 1975) defines the *ARF* as "the ratio of rainfall depth over an *AREA* to the rainfall depth of the same duration and return period at a representative point in the *AREA*". The FSR values of *ARF* were adopted in the FEH. These values have been expressed mathematically by Keers and Wescott (1977) as

$$ARF = 1 - bD^{-a} \tag{4.4}$$

where D is the duration of the design rainfall and a and b are parameters derived by Keers and Wescott (1977) as a function of catchment $AREA$ and found in Table 4.1.

Table 4.1 *Areal reduction factor parameters (Keers and Wescott, 1977)*

AREA A **(km²)**	***a***	***b***
$A \le 20$	$0.40 - 0.0208 \ln[4.6 - \ln[A]]$	$0.0394\,A^{0.354}$
$20 < A < 100$	$0.40 - 0.00382\,(4.6 - \ln[A])^2$	$0.0394\,A^{0.354}$
$100 \le A < 500$	$0.40 - 0.00382\,(4.6 - \ln[A])^2$	$0.0627\,A^{0.254}$
$500 \le A < 1000$	$0.40 - 0.0208 \ln[\ln[A] - 4.6]$	$0.0627\,A^{0.254}$
$1000 \le A$	$0.40 - 0.0208 \ln[\ln[A] - 4.6]$	$0.1050\,A^{0.180}$

A subsequent review (Institute of Hydrology, 1977) concluded that the FSR values of ARF were appropriate for use in FSR design methods and that no evidence of geographical variation was found. However, the same review found ARF to decrease with increasing return period, considering return periods ranging from 2 to 20 years, but recommended that this dependency should be neglected for practical purposes as the effect was considered small compared to the influence of using relatively short data records and other simplifying assumptions. Despite suggestions in Institute of Hydrology (1977) that estimates of ARF should be revisited once longer rainfall records were made available, no such work has been undertaken to date.

4.3.5 Seasonal correction factors

The ReFH method has adopted the FEH DDF model as the basis for deriving design rainfall, including the definitions of ARF and storm profiles. The added emphasis on summer and winter design inputs made it necessary the need for specifying seasonal design rainfall input. A seasonal correction factor (SCF) is introduced, converting the FEH DDF estimate of design rainfall based on annual maximum rainfall into an estimate of seasonal design rainfall through simple multiplication as

$$P_{d,i} = SCF_{d,i}\,P_{d,A}\,, \qquad i = \text{summer, winter} \tag{4.5}$$

where $P_{d,i}$ is the d-hour/day design rainfall in the i^{th} season (summer or winter) for a specified return period, $P_{d,A}$ is the corresponding d-hour/day design rainfall based on annual maximum rainfall and SCF_d is a correction factor depending on location, season, duration and selected return period. A detailed description of the data and analysis used for development of generic expressions of the summer and winter seasonal correction factors are given by Kjeldsen *et al.* (2006).

Functional relationships between the seasonal correction factors obtained from the observed rainfall series and the $SAAR$ catchment description were developed for durations of 1, 2 and 6 hours and 1 day, enabling users to estimate the seasonal correction factor at any catchment or location identified on the FEH CD-ROM where a $SAAR$ value is available. The form of the functional relationships were used for summer and winter respectively, but both seasons are described using two-parameter functions given as

$$SCF_d = \begin{cases} \alpha\,SAAR + \phi & \text{summer} \\ (1 - \exp[\varphi SAAR])^{\psi} & \text{winter} \end{cases} \tag{4.6}$$

For the summer relationship, a constraint was included in the parameter estimation that for $SAAR$ = 500 mm the seasonal correction factor equals one, i.e. $1 = \alpha\,500\text{ mm} + \beta$. The parameter estimates of the predictive models in Equation 4.6 are shown in Table 4.2.

Table 4.2 Seasonal correction factor parameters

	Summer		Winter	
Duration	α	β	φ	ψ
1 hour	$-8.03\ 10^{-5}$	1.04	0.0004	0.4000
2 hour	$-6.87\ 10^{-5}$	1.03	0.0006	0.4454
6 hour	$-4.93\ 10^{-5}$	1.02	0.0009	0.4672
1 day	$-10.26\ 10^{-5}$	1.05	0.0011	0.5333

Seasonal correction factors for durations other than found in Table 4.2 can be obtained by interpolation between the values in Table 4.2. Seasonal correction factors for durations of more than 1 day are probably rare in practice, but the current recommendation is to use the 1-day values in such circumstances. However, the subject of frequency analysis of seasonal extreme rainfall is an issue where further research is ongoing. The relationships between *SCF* and *SAAR* for both summer and winter are shown in Figure 4.3 for each of the four durations in Table 4.2.

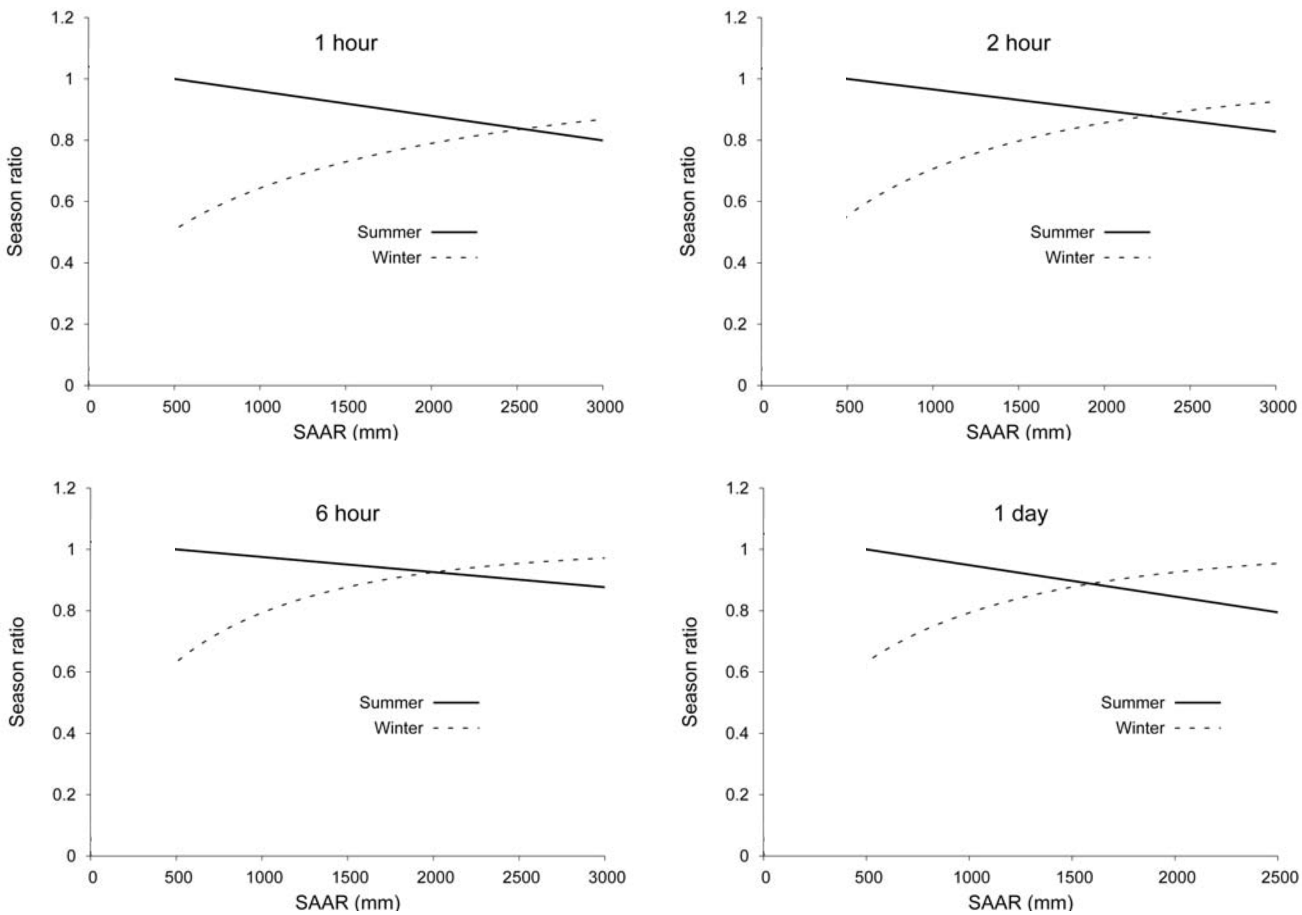


Figure 4.3 *Seasonal correction factors for summer and winter*

4.3.6 Design storm profiles

The ReFH rainfall-runoff model, as well as the FSR/FEH rainfall-runoff model, attempts to model the temporal distribution of the rainfall-runoff processes. It is therefore necessary to consider methods for obtaining hyetographs of the design rainfall events. The revitalised method has adopted the 75% winter and 50% summer profiles used in the FSR/FEH rainfall-runoff method.

The adopted design storm profiles are symmetric and single peaked. Their shape does not vary with storm duration and is considered invariant with location, although it is recognised that profiles in upland areas tend to be less peaked (Faulkner, 1999). On predominantly rural catchments (*URBEXT* < 0.125), floods normally occur during the winter season and the method has adopted the 75% winter profile which is on average more peaked than 75% of observed UK winter storms (NERC, 1975). On catchments characterised as being urbanised (0.125 ≤*URBEXT* ≤0.50) the 50% summer profile has been adopted, which is on average more peaked than 50% of observed UK summer storms (Institute of Hydrology, 1979).

The two rainfall profiles are shown in Figure 4.4 and the cumulative profiles in Figure 4.5. The 50% profile is more peaked than the 75% winter profile, because of the prevalence of intense convective storms in the summer. Faulkner (1999) reiterated the recommendations made in FSR that these profiles are recommended for duration "up to several days" despite being based on information from 24-hour storms only. However, design storm profiles for long duration storms is a topic for further research and attention is drawn to the critical review by Faulkner (1999).

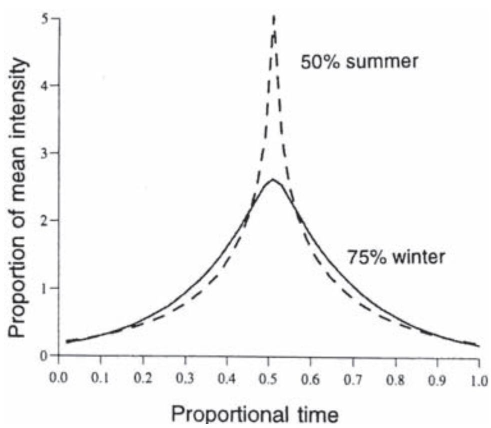


Figure 4.4 *Design rainfall profiles for summer and winter, drawn as normalised hyetographs*

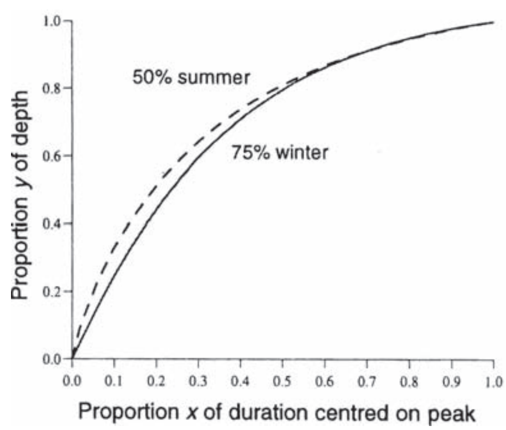


Figure 4.5 *Design rainfall profiles, drawn as cumulative proportions of depth, centred on peak*

A model for the design profiles was developed as part of the implementation of the FSR method in the Micro-FSR software package (Institute of Hydrology, 1991). The proportional depth of rain, y, falling in the temporal proportion, x, of the total duration, centred on the peak is given as

$$y = \frac{1 - a^{z}}{1 - a} \tag{4.7}$$

where $z = xb$ and a and b are profile specific constants listed in Table 4.3.

Note that the formula in Equation 4.7 gives unrealistically large values for the 50% summer profile when a short time step is used.

Table 4.3 Parameters for derivation of design profiles

Profile	*a*	*b*
75% Winter	0.060	1.026
50% Summer	0.100	0.815

Example 4.2
Calculation of design rainfall depth *P*

Catchment: Mellte at Pontfeddfechan (58006) (IHDTM grid ref. 291350 208100)

Relevant catchment descriptors and other information from FEH CD-ROM v1.0:
$URBEXT_{1990} = 0.000$, $D = 6.5$ hours, $AREA = 65.38$ km^2

Select flood return period

$T = 50$ years

Abstract 50-year 6.5-hour rainfall using the FEH DDF model (§4.3.3)

RDDF is abstracted from the FEH CD-ROM

$RDDF = 88.2$ mm

Calculate the Areal Reduction Factor (§4.3.4)

The *ARF* appropriate to the catchment area and storm duration is obtained through Equation 4.4

$ARF = 0.918$

Calculate Seasonal Correction Factor (§4.3.5)

With an $URBEXT_{1990}$ value of $0.000 < 0.125$, the design flood event should be estimated based on winter season design input. Using Equation 4.6 combined with a storm duration of $D = 6.5$ hours, linear interpolation in Table 4.2 is necessary to obtain the two parameters φ and ψ for the winter season model

$\varphi = 9.06 \times 10^{-4}$
$\psi = 0.4690$

Having obtained these parameters, the *SCF* factor can be calculated

$SCF = 0.92$

Calculate design rainfall depth *P*

The design rainfall depth *P* is the *T*-year *D*-hour catchment rainfall for the considered season, calculated by scaling *RDDF* by the areal reduction factor and the seasonal reduction factor

$P = RDDF \times ARF \times SCF$

$P = 74.4$ mm

A critical review of the FSR storm profiles was presented by Faulkner (1999). In general, the profiles have been criticised for being too simple, especially due to the imposed symmetry as well as for the profiles being too peaked. For the special case of large reservoired catchments, the FSR profiles have been deemed particularly unsuitable. On such catchments, the critical rainfall duration can be as long as ten days, reflecting sensitivity to a rapid succession of storms which can cause reservoir levels to build up over several days (Faulkner, 1999). For the FSR/FEH method, The Institution of Civil Engineers (1996) recommended the use of temporal profiles of the severest sequence of storms of the required duration observed locally.

Example 4.3
Derivation of design rainfall profile

Catchment: Mellte at Pontfeddfechan (58006) (IHDTM grid ref. 291350 208100)

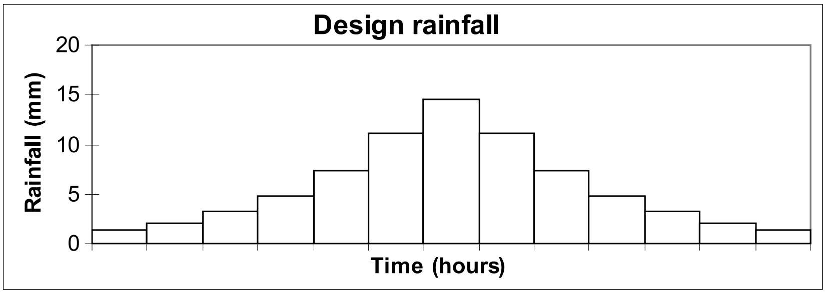
Relevant catchment descriptors and other information from FEH CD-ROM v1.0:
$URBEXT_{1990} = 0.000$, $P = 74.4$ mm, $D = 6.5$ hours, $\Delta t = 0.5$ hours

The design rainfall depth P is distributed within the design storm duration D using the appropriate design storm profile. $URBEXT < 0.125$ so the appropriate profile is the 75% winter profile from Figure 4.4:

$D = 6.5$ hours and $\Delta t = 0.5$ hours, so a total of 13 rainfall block intervals, each with a duration equivalent to a fraction 1/13 or 7.7% of D.

The storm is centred on the 0.5 hour between 3 and 3.5 hours after storm commencement. This peak period represents 1/13 or 7.7% of D and the 75% winter profile specifies that this contains 20% of P.

The central three periods of the storm represent 3 / 13 or 23.1% of the storm duration. This contains 49.5% of P. Of this, 20% occurs in the central 0.5 hours; the remaining 29.5% of the depth (i.e. 49.5% – 20%) is divided between the two outer 0.5 hour periods, with 14.7% of P in each. The rest of the profile is constructed in a similar way, as shown below.



Interval	1	2	3	4	5	6	7	8	9	10	11	12	13
Rain *(mm)*	1.3	2.0	3.2	4.9	7.4	11.1	14.5	11.1	7.4	4.9	3.2	2.0	1.3

Note that the design rainfall is centred on the peak rainfall interval and symmetrical.

4.4 Design soil moisture content

The catchment average soil moisture content at the start of the flood event is denoted C_{ini} and is measured in millimetres. The catchment wetness is an important factor influencing the runoff volume as specified in §2.3. However, in the design event method there is a need to make simplifying assumptions. The design values of C_{ini} is estimated for the winter and summer seasons, respectively, as

$$\begin{aligned} C_{ini,winter} &= \frac{C_{\max}}{2}(1.20 - 1.70BFIHOST + 0.82PROPWET) \\ r^2 &= 0.53, \quad n = 93 \\ C_{ini,summer} &= \frac{C_{\max}}{2}(0.90 - 0.82BFIHOST - 0.43PROPWET) \\ r^2 &= 0.49, \quad n = 7 \end{aligned} \tag{4.8}$$

where $C_{max} / 2$ is the catchment average soil moisture capacity, *BFIHOST* is the baseflow index derived from HOST classes and *PROPWET* is the proportion of time catchment soils are wet as described by Bayliss (1999). For certain catchments, the design values of C_{ini} derived using Equation 4.8 might be negative, in which case C_{ini} is set equal to zero.

4.5 Initial baseflow

The baseflow model described in §2.5 needs an initial value in order to derive a hydrograph of the baseflow response. The initial value of baseflow (BF_0) is measured in m^3s^{-1} and is estimated for the winter and summer season, respectively, as

$$\begin{aligned} BF_{0,winter} &= (63.8(C_{ini} - 120.8) + 5.54SAAR)10^{-5}AREA \\ r^2 &= 0.47, \quad n = 752 \\ BF_{0,\,summer} &= (33.9(C_{ini} - 85.4) + 3.14SAAR)10^{-5}AREA \\ r^2 &= 0.42, \quad n = 431 \end{aligned} \tag{4.9}$$

where C_{ini} is the initial soil moisture content, *SAAR* is standard average annual rainfall (mm) and *AREA* is catchment area (km^2). For certain catchments, the values of BF_0 obtained using Equation 4.9 might be negative, in which case BF_0 is set equal to zero.

4.6 Adjustment coefficient

For the ReFH design package to simulate design flood events with peak flow values corresponding to the results obtained from the statistical method, a correction factor α_T has been introduced. The rationale behind the introduction of the correction factor is discussed in Appendix D. In practice, α_T is applied to the first time step in the loss model as

$$q_t/P_t = \begin{cases} \alpha_T\left(\dfrac{C_{ini}}{C_{\max}}\right) + \dfrac{P_t}{2C_{\max}} & t = 1 \\ \left(\dfrac{C_{t-1}}{C_{\max}}\right) + \dfrac{P_t}{2C_{\max}} & t = 2, 3\ldots \end{cases} \quad \text{and } C_{t+1} = C_t + P_t \tag{4.10}$$

where the soil moisture accounting starts from $\alpha_T\, C_{ini}$. The value of α_T depends on season (winter / summer) and the considered return period and can be estimated from Figure 4.6.

Note that the ReFH design package has been calibrated only to a return period of 150 years.

Two simple power functions were fitted to the data in Figure 4.6 allowing estimation of the α_T correction factor from return period:

$$\alpha_{T,\ winter} = \begin{cases} 1 & T < 5 \\ 1.166\,T^{-0.073} & T \geq 5 \end{cases}$$
$$\alpha_{T,\ summer} = \begin{cases} 1 & T < 5 \\ 1.444\,T^{-0.182} & T \geq 5 \end{cases} \qquad (4.11)$$

where T is return period. For return periods less than 5 years, the α_T correction factor is set equal to 1 in both seasons.

Example 4.4
Derivation of catchment design input parameters

Catchment: Mellte at Pontfeddfechan (58006) (IHDTM grid ref. 291350 208100)

Relevant catchment descriptors and other information from FEH CD-ROM v1.0:

BFIHOST = 0.322, *SAAR* = 1981 mm, *AREA* = 65.38 km^2, $URBEXT_{1990}$ = 0.000, PROPWET = 0.62, C_{max} = 293 mm (obtained from Appendix C), Return period T = 50 years,

URBEXT < 0.125 so the appropriate season is the winter season when estimating initial soil moisture content (C_{ini}), initial baseflow (BF_0) and the correction factor (α_T).

Calculate initial soil moisture content (§4.5)

The initial soil moisture content C_{ini} is calculated from Equation 4.8

C_{ini} = 170 mm

Calculate initial baseflow (§4.6)

$URBEXT_{1990}$ < 0.125 so the appropriate season is the winter season and BF_0 is calculated from Equation 4.9 using C_{ini} as obtained above

$BF_0 = 9.2\ m^3s^{-1}$

Estimating the correction factor (§4.7)

A value of the correction factor for the winter season and for a 50-year return period is obtained from Equation 4.11

$\alpha_{50} = 0.88$

4.7 Derivation of T-year flood events

The T-year design flood event is estimated from the input design rainfall event and the initial soil moisture content by the following steps

- apply the loss model to the total rainfall hyetograph to derive the net rainfall hyetograph;
- convolute the unit hydrograph with the net rainfall hyetograph to derive the direct response runoff hyetograph;

- calculate the baseflow hydrograph, and
- add to the direct runoff hydrograph to obtain the total runoff hydrograph.

The peak flow values of the T-year design flood events can be plotted against their corresponding return period to produce a flood frequency curve for the catchment considered.

4.7.1 Derivation of net rainfall hyetograph

The values of rainfall depth P, the initial soil moisture content C_{ini} and the correction factor α_T, determined in §4.4, §4.5 and §4.6, can be substituted into the loss model given in Equation 4.10 which allows for the calculation of the net rainfall hyetograph. There are two options for the loss model. Firstly, it can compute the losses in sequential time steps or, secondly, it can calculate a single loss of the entire storm, which will yield a symmetrical net hyetograph. The first option is recommended for use in the design package.

4.7.2 Derivation of the direct runoff hydrograph

The direct runoff hydrograph is the product of convoluting the unit hydrograph in §2.4 with the net rainfall hyetograph from §4.3 through use of Equation 2.9. The background to the convolution procedure is described in §2.4 and an example is shown below (Example 4.6).

Example 4.5
Derivation of net rainfall hyetograph for T = 50 year storm

Catchment: Mellte at Pontfeddfechan (58006) (IHDTM grid ref. 291350 208100)

Relevant information
$D = 6.5$ hours, $P = 74.4$ mm, $a_{50} = 0.88$, $C_{max} = 293$ mm, $C_{ini} = 170$ mm

By applying the ReFH loss model for design flood estimation from Equation 4.10 is successive steps, the following net rainfall hyetograph is obtained:

Interval	Total rainfall *mm*	Percentage runoff	Net rainfall *mm*	Soil moisture *mm*
1	1.3	0.510	0.7	150.2 (αC_{ini})
2	2.0	0.516	1.1	152.3
3	3.2	0.525	1.7	155.4
4	4.9	0.539	2.6	160.3
5	7.4	0.560	4.1	167.7
6	11.1	0.591	6.6	178.8
7	14.5	0.635	9.2	193.3
8	11.1	0.679	7.6	204.5
9	7.4	0.711	5.3	211.9
10	4.9	0.731	3.6	216.8
11	3.2	0.745	2.4	219.9
12	2.0	0.754	1.5	222.0
13	1.3	0.760	1.0	223.3

Note how the percentage runoff increases as the soil gets increasingly wet during the storm event, which results in a non-symmetric net rainfall hyetograph.

4.7.3 Derivation of baseflow hydrograph

Calculation of the baseflow hydrograph requires an estimate of the initial baseflow value BF_0 as described in §4.5. The baseflow model derives the baseflow hydrograph using a recursive model where baseflow at a specific time depends on the baseflow in the previous time step as well as the direct runoff at the same time step, as shown in Example 4.6.

4.7.4 Derivation of total runoff hydrograph

The total runoff hydrograph is obtained by simply adding the baseflow hydrograph to each ordinate of the direct runoff hydrograph, as shown in Example 4.6.

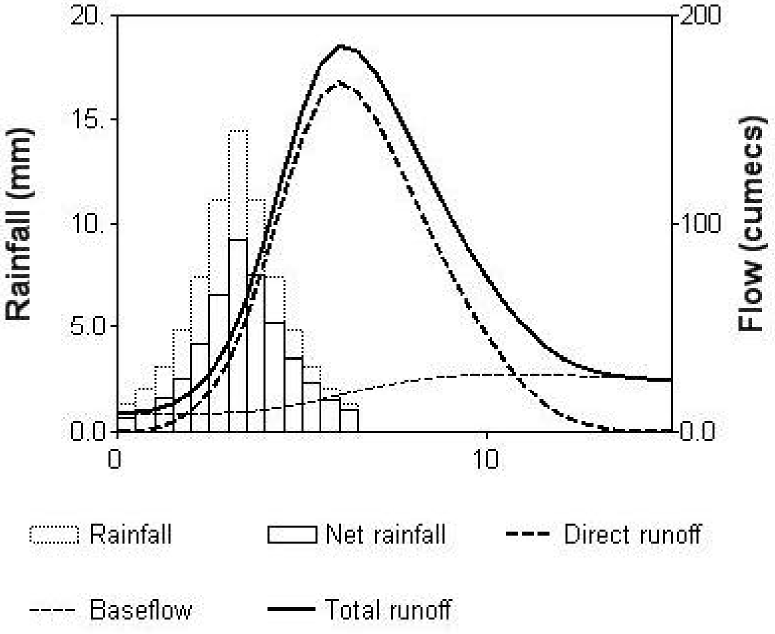
Example 4.6
Derivation of direct runoff, baseflow and total runoff hydrographs

Catchment: Mellte at Pontfeddfechan (58006) (IHDTM grid ref. 291350 208100)

Interval	Total rainfall *mm*	Net rainfall *mm*	Direct runoff m^3s^{-1}	Baseflow m^3s^{-1}	Total runoff m^3s^{-1}
0.5	1.3	0.7	0.0	9.2	9.2
1.0	2.0	1.1	0.4	9.1	9.5
1.5	3.2	1.7	1.8	9.0	10.7
2.0	4.9	2.6	4.7	8.9	13.6
2.5	7.4	4.1	10.2	8.8	19.0
3.0	11.1	6.6	19.4	8.9	28.3
3.5	14.5	9.2	33.6	9.2	42.8
4.0	11.1	7.6	55.1	9.7	64.7
4.5	7.4	5.3	83.1	10.5	93.6
5.0	4.9	3.6	113.6	11.8	125.4
5.5	3.2	2.4	141.6	13.5	155.1
6.0	2.0	1.5	161.3	15.5	176.8
6.5	1.3	1.0	168.0	17.6	185.6
7.0			163.1	19.8	182.8
7.5			150.2	21.8	171.9
8.0			132.5	23.5	156.0
8.5			113.4	24.9	138.3
9.0			94.6	26.0	120.6
9.5			76.7	26.9	103.6
10.0			60.6	27.4	88.0
10.5			46.2	27.8	74.0
11.0			33.4	27.9	61.4
11.5			22.6	27.9	50.5
12.0			14.1	27.7	41.9
12.5			8.3	27.5	35.7
13.0			4.5	27.1	31.6
13.5			2.2	26.7	29.0
14.0			0.9	26.4	27.3
14.5			0.2	25.9	26.2

Example 4.6 (continued)
Derivation of direct runoff, baseflow and total runoff hydrographs

Catchment: Mellte at Pontfeddfechan (58006) (IHDTM grid ref. 291350 208100)



Chapter 5 Application – considerations and limitations

5.1 Introduction

When applying the revitalised FSR/FEH rainfall-runoff method to generate design flood hydrographs it is important to be aware of the limitations and possible caveats of the method. The purpose of this chapter is to give guidance on issues where problems might arise. The chapter is divided into two parts. The first section (§ 5.2) highlights issues of practical concern when applying the method to generate design flood hydrographs. The second section (§ 5.3) is concerned with issues for which the method is likely to be used but for which no new research has been carried out to provide supportive guidelines.

5.2 User guidance

The standard revitalised FSR/FEH design method as outlined in Chapter 4 can reasonably be applied to most catchments in the UK that are at least 0.5 km^2 in size. When using the design model it is important to ensure that the result is indeed a design hydrograph of the desired return period. Considering that the method was calibrated using a finite sample of 101 catchments throughout the UK, it is inevitable that users will encounter catchments where local peculiarities are not properly accounted for in the ReFH model structure, or encompassed in the data set used for calibrating the design method. This section highlights issues of practical concern that might assist (and advise) in the application of the method.

5.2.1 Seasonality

According to FEH Vol. 4 (Houghton-Carr, 1999), rural catchments ($URBAN_{1990}$ < 0.125) tend to respond to longer duration rainfall events, more often associated with frontal rainfall which is more prevalent in the winter season (November – April). Urbanised catchments ($URBEXT_{1990} \geq 0.125$), on the other hand, tend to respond to short duration intense rainfall events, such as the convective storms often encountered during the summer months (May to October). This effect is recognised by the revitalised FSR/FEH rainfall-runoff method, and a set of standard design input values (initial baseflow, BF_0, initial soil moisture content, C_{ini}, seasonal rainfall correction factor, SCF, and the calibration coefficient, α_T) were developed accordingly for each of the two seasons.

When using the design model on a particular catchment, the choice of design input values should be based on the degree of urbanisation of the catchment, not on which of the two seasons yields the higher peak flow value. Using the summer design conditions on a rural catchment is applying the design model on a catchment type for which it was not calibrated and vice versa. In addition, the summer design conditions have been found to give unrealistic results for groundwater dominated catchments, i.e. catchments with high BFIHOST values.

5.2.2 Range of return periods

The design model was calibrated using the calibration parameter, α_T, for return periods in the range 5 to 150 years. For return periods of less than 5 years, the calibration parameter is set to a fixed value of 1. A generalised power function was fitted to the calibration data to allow users to extrapolate to return periods beyond the 150-year limit. For such extreme events, however, the method offers no guarantee that the resulting design flood estimate is of the desired return period.

Similarly, no investigation of the values of the calibration parameter for events with a return period of less than one year was conducted. The general rules outlined above indicate that a calibration factor of $\alpha_T = 1$ could be applied but no guarantee can be given that the resulting design floods are of the desired return period.

5.2.3 Catchment types

The ReFH model is a generic rainfall-runoff model and has been found to perform well on a range of different catchments. However, it is important to recognise that the statistical analyses linking model parameters to catchment descriptors were carried out using a limited number (101) of catchments (see Appendix C). Prediction of model parameters and general model performance is increasingly uncertain when applied outside the range represented by the catchments in the calibration dataset. Catchment types that are likely to be of particular concern are small catchments, urbanised catchments and permeable catchments.

The smallest catchment included in the model development was 3.5 km^2. While there are no theoretical reasons why the ReFH model should not perform adequately on smaller catchments, this has not been verified through modelling studies. With regard to the upper limit of catchment area, the FEH recommendation that the FSR/FEH rainfall-runoff method should not be used for catchments larger than 1000 km^2 has been retained for the ReFH model since the concept of a single catchment-wide design storm is less realistic for large catchments. The largest catchment used in the development of the method was 511 km^2.

It is generally expected that the main effects of urbanisation on flood hydrology are to reduce the catchment response time and to increase the runoff volume. While the first effect is included in the prediction equation for the time-to-peak (Tp) parameter, the effect on runoff volume (in terms of an effect on the loss model parameter, C_{max}) could not be detected in the available data. Therefore, in its current formulation the ReFH model is not well suited to assess the effect of urbanisation on flood peaks and flood runoff volumes.

As with the FSR/FEH rainfall-runoff method, modelling design floods on permeable catchments remains a problem when using the revitalised FSR/FEH rainfall-runoff method. The ReFH model was found to perform poorly on permeable catchments as the typically subdued runoff response to rainfall input from this type of catchment results in unrealistically large values of the loss model parameter, C_{max} and unrealistically values of C_{ini} (to low in winter and too high in summer). Guidance in Volume 1 of the FEH (Reed, 1999) suggests that a statistical approach, rather than the rainfall-runoff method, is preferred when the catchment is highly permeable.

When estimating the ReFH model parameters at ungauged sites it is advisable to compare the catchment descriptors at the site of interest to the range of descriptor-values (Tables 3.2 to 3.5) that were used in the calibration of the predictor equations in §3.3. If a catchment is particularly unusual, it is recommended that extra effort should be made to identify and collect local observed data.

5.3 Other applications

The FSR rainfall-runoff method was originally published in 1975 and has been used extensively in engineering and research for the last 30 years. Consequently, a large and very active user community exists along with numerous publications providing user guidance and information on model performance. A similar wealth of experience is not available for the revitalised FSR/FEH rainfall-runoff method since the method is newly developed. This section aims to highlight issues where the revitalised FSR/FEH rainfall-runoff method is likely to be used but where no specific research has been conducted at present. The issues include return period assessment of notable flood events, probable maximum flood estimation, reservoir flood estimation and disparate subcatchments and land use effects.

5.3.1 Return period assessment of notable flood events

Knowledge of the event severity is important when assessing the performance of existing flood defences and in catchment flood management planning. Therefore, following a significant flood event it might be necessary to estimate the return period of that event (Houghton-Carr, 1999).

For an ungauged catchment, the FSR approach to assessing the return period of an individual flood event using the rainfall-runoff method consists of three steps:

- Construct the catchment flood frequency curve (FFC) using the FSR/FEH rainfall-runoff method;
- Derive the total runoff hydrograph of the individual flood event under consideration based on observed values of antecedent soil moisture and rainfall hyetograph;
- Compare the simulated peak flow of the observed event with the derived FFC and estimate the associated return period.

In principle, a similar procedure can be used in combination with the revitalised FSR/FEH rainfall-runoff method, where the catchment flood frequency curve is derived using the method as outlined in Chapter 4, and the total runoff hydrograph of the flood event, based on observed values of antecedent soil moisture and hyetograph, is simulated as outlined above. However, it is important to remember that the revitalised FSR/FEH method has only been calibrated up to a return period of 150 years. As the method was calibrated by comparing the derived FFC with the FFC obtained from pooled statistical analysis, the peak flow of the simulated event can alternatively be compared to the FFC derived from the FEH statistical method (Robson and Reed, 1999) for return period assessment.

Note that the return period assessment as outlined in this section is considering only the peak flow of the individual flood event. Other aspects such as flood volume and duration have not been considered.

5.3.2 Probable maximum flood estimation

As documented by the FSR (I.6.8.3) and Houghton-Carr (1999), the FSR rainfall-runoff method is able to simulate a probable maximum flood (PMF) using probable maximum precipitation (PMP) as input. The FSR recommended that a number of adjustments should be made to the FSR rainfall-runoff model in order to maximise the flood-generating mechanisms when simulating a PMF. The adjustments are applied to the antecedent soil moisture, the unit hydrograph and the storm profile. Despite emphasising that these recommendations were preliminary and pending further investigations, they all appear 25 years later in the restatement of the method (Houghton-Carr, 1999), highlighting the lack of research undertaken on this very important topic.

The fundamental differences between the FSR model and the revitalised FSR/FEH method make a direct transfer of these guidelines a non-trivial exercise. The design package in the revitalised FSR/FEH method is based on the use of a correction factor in the soil moisture accounting module. This correction factor has been calibrated to a return period of 150 years and it is not known at present what values would be suitable for PMF estimation.

5.3.3 Reservoir flood estimation

Design flood estimation has traditionally played a very important role in reservoir safety assessment in the UK since the publication of the FSR (ICE, 1996). It is important to remember that the revitalised FSR/FEH method has been calibrated to produce design flood events with a return period of up to 150 years. This is probably lower than the return period of design floods required for most reservoir studies. In fact, the ICE guidelines are based on design floods with a return period ranging from a lower limit of 150 years up to the physical limit (ICE, 1996). Houghton-Carr (1999) provides a comprehensive review of reservoir flood estimation based on rainfall-runoff modelling.

5.3.4 Disparate subcatchments

It is anticipated that the revitalised FSR/FEH rainfall-runoff method will be used in a semi-distributed context, where runoff is modelled from a number of disparate subcatchments representing more local features than possible with a single lumped catchment model. This type of approach is often used when flood event hydrographs are required as inflow to a hydrodynamic river model at different locations.

Contributions to a flood event from different parts of a catchment depend on the configuration of the drainage network and the local physical features of the catchment, as well as the spatial variability of the rainfall. A site of interest located immediately downstream of the confluence between two watercourses is an example of a case where an analysis based on disparate subcatchments might be more appropriate than using a single lumped catchment. Other examples include catchments where rainfall and/or flood-generating mechanisms vary spatially and situations involving catchwaters and other diversions from neighbouring catchments. Guidelines for the use of event-based rainfall-runoff methods in a semi-distributed mode to model disparate subcatchments are given by Houghton-Carr (1999). These guidelines, developed for the FSR/FEH method, are equally applicable to the revitalised FSR/FEH rainfall-runoff method.

5.3.5 Land-use effects

The impact of land use and land-use changes on the physical flood-generating mechanisms is a complex issue that can be considered at a multitude of spatial and temporal levels (Calder, 1993). In a review of the impact of land-use management on flood generation in the UK, O'Connell *et al.* (2005) distinguish between local and catchment scales, where the latter is considered to apply to catchments larger than 10 km^2.

No procedures are currently available for assessing the impacts of land-use changes and management on the resulting flood hydrology using the revitalised FSR/FEH rainfall-runoff method. An interim method was developed to be used with the existing FSR/FEH rainfall-runoff method (Packman *et al.*, 2004a) where the effect of land use was assessed by adjusting the percentage runoff and time-to-peak parameters. The procedure uses GIS data on HOST class and land-use type to define 'worst case' or 'fully degraded' impact of agricultural intensification on time to peak and standard percentage runoff. A decision support matrix (the FARM tool) is used to assess the likely degree of degradation due to agricultural intensification within the catchment.

As mentioned above, the procedures were developed for the original FSR/FEH rainfall-runoff method, and their effect on the revitalised FSR/FEH method has not been tested. However, speculative changes to HOST class and time-to-peak should be just as applicable to the revitalised FSR/FEH method. Indeed, the revitalised FSR/FEH method's use of BFIHOST in preference to SPRHOST to estimate loss rates (C_{max}) in Equation 3.18 was based in part on the findings by Packman *et al.* (2004b) of inconsistency between SPR and HOST class under changing soil compaction scenarios. As observed values of the baseflow index (BFI) can be derived for many more catchments than standard percentage runoff, the BFIHOST catchment descriptor is a better defined property than the corresponding SPRHOST catchment descriptor, and should therefore give a more accurate assessment of the runoff potential.

Chapter 6 Worked examples

6.1 Introduction

This chapter combines the procedures outlined in Chapters 2 to 4 through the presentation of two worked examples illustrating different applications of the revitalised FSR/FEH rainfall-runoff method. Section 6.2 covers the estimation of the *T*-year design flood event and §6.3 illustrates simulation of a notable flood event. In each example, the specific numerical values are given on the right hand side of the page, alongside the description of the general procedure. In general, it is recommended that the calculations are carried out in appropriate software packages to minimise the risk of errors.

6.2 Design flood estimation

Catchment: Salwarpe at Harford Mill (54011) (IHDTM grid ref. 386850 261950) shown in Figure 6.1.

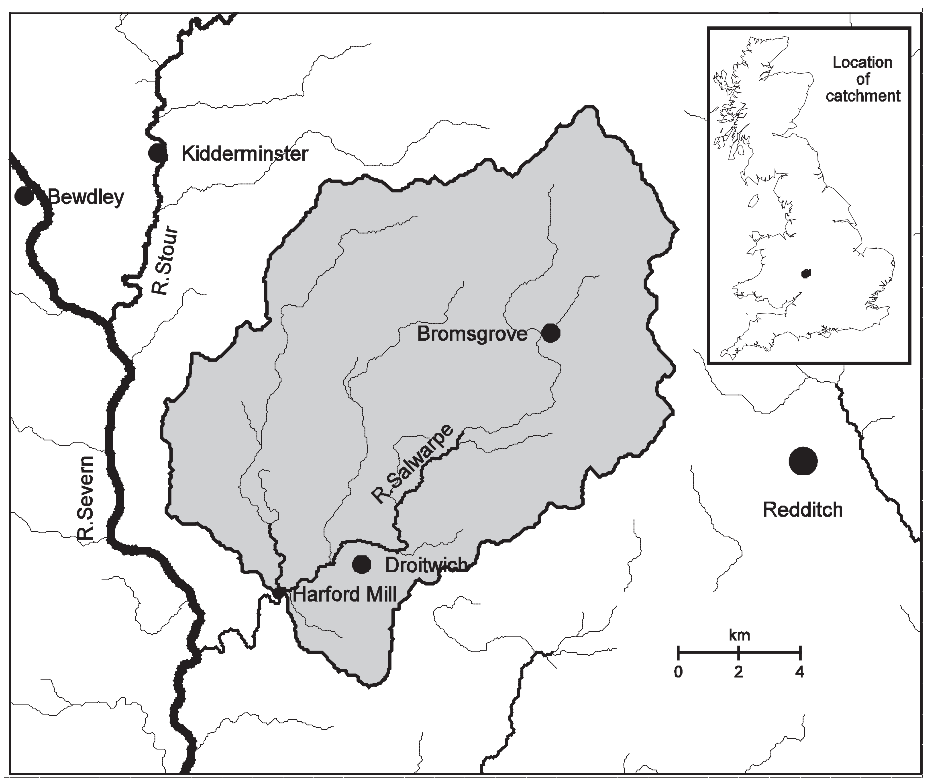


Figure 6.1 *Salwarpe at Harford Mill (54011)*

Relevant catchment descriptors and other information from FEH CD-ROM v1.0:

$AREA$ = 186.20 km^2, $URBEXT_{1990}$ = 0.0496, $SAAR$ = 666 mm, $BFIHOST$ = 0.523
FEH DDF design rainfall parameters for catchment:
(c, d_1, d_2, d_3, e, f) = (-0.027, 0.332, 0.346, 0.299, 0.295, 2.443)

6.2.1 Estimation of ReFH model parameters

The ReFH model parameters (C_{max}, *Tp*, *BL* and *BR*) are derived from the flood event analysis results in Appendix C:

C_{max} = 333 mm
Tp = 9.56 hours
BL = 26.5 hours
BR = 0.54

6.2.2 Calculation of design storm duration D

Considering that 10% of *Tp* = 9.56 hours is 0.96 hours, a data interval of 1.0 hours is appropriate.

The design storm duration *D* is calculated from *Tp* and *SAAR* using Equation 4.1:

$$D = Tp\left(1 + \frac{SAAR}{1000}\right)$$

D = 15.9 hours

In this instance, Δt = 1 hour, so *D* is rounded down to 15 hours, which is the nearest odd integer multiple of Δt:

D = 15 hours

6.2.3 Calculation of design storm depth P

As the catchment has an $URBEXT_{1990} < 0.125$, the winter design input values should be used in determination of the *T*-year design flood event.

Decide upon flood return period

T = 100 years

Abstracting *T*-year *D*-hour design rainfall from FEH DDF model from Equation 4.3:

$$\ln[R] = \ln[R_{12}] + (cy + d_2)(\ln[D] - \ln[12]$$

RDDF = 78.7 mm

The areal reduction factor (*ARF*) appropriate to the catchment area and storm duration is obtained from Equation 4.4:

$$ARF = 1 - bD^{-a}$$

where the parameters *a* and *b* are obtained from Table 4.1.

ARF = 0.92

The seasonal correction factor (*SCF*) is obtained by first obtaining the winter parameters φ and ψ from interpolation in Table 4.2:

$\varphi = 10.00\ 10^{-4}$
$\psi = 0.5003$

The *SCF* is obtained from the winter part of Equation 4.5:

$$SCF_{15\ hours} = (1 - \exp[\varphi SAAR])^{\psi}$$

SCF = 0.70

The final estimate of design rainfall depth is obtained as

$$P = RDDF \times ARF \times SCF = 78.7 \times 0.92 \times 0.70$$

P = 50.7 mm

6.2.4 Derivation of design storm profile

The design storm depth P is distributed within the design storm duration D using the appropriate design storm profile as described by Houghton-Carr (1999).

Since $URBEXT_{1990} = 0.0496 < 0.125$, the appropriate profile is the 75% winter profile from Figure 4.4:

Duration $D = 15$ hours and $\Delta t = 1$ hour, so each rainfall block of interval 1.0-hour will have a duration equivalent to a fraction 1/15 or 6.7% of D.

The storm is centred on the 1.0-hour period occurring between 7 and 8 hours after storm commencement. This peak period represents 1/15 or 6.7% of D and the 75% winter profile specifies that this contains 17% of P.

The central three periods of the rainfall event represent 3/15 or 20% of the rainfall duration. This contains 44 % of the P. Of this, 17 % occurs in the central 1.0-hour; the remaining 27% of the depth (i.e. 44 % – 17 %) is divided between the two outer 1.0-hour periods, with 13.5% of P in each. The rest of the profile is constructed in a similar way.

6.2.5 Derivation of design initial soil moisture content C_{ini}

The design initial soil moisture content C_{ini} is obtained for the appropriate values of $SAAR$ and $BFIHOST$ from Equation 4.8 for the winter conditions

$$C_{ini,\ \mathrm{winter}} = \frac{333}{2}\ (1.20 - 1.70\ BFIHOST + 0.82\ PROPWET) \qquad C_{ini} = 90\ \mathrm{mm}$$

6.2.6 Derivation of net event hyetograph

The net hyetograph is derived by applying the ReFH loss model in form of Equation 4.10. The loss model requires estimates of C_{ini} derived above and an α-factor depending on the selected return period and estimated Equation 4.11

$$\alpha_{100} = 1.166 \times 100^{-0.073} \qquad \alpha = 0.83$$

By applying the ReFH loss model for design flood estimation in Equation 4.10 in successive steps, the net rainfall hyetograph shown in Table 6.1 is obtained.

Table 6.1 *Calculation of net hyetograph*

Interval	Total rainfall *mm*	Percentage runoff Equation 10	Net rainfall *mm*	Soil moisture content *mm*
1	0.8	0.226	0.2	75.6
2	1.1	0.229	0.3	76.7
3	1.6	0.233	0.4	78.3
4	2.3	0.239	0.6	80.7
5	3.4	0.247	0.8	84.1
6	4.9	0.260	1.3	88.9
7	6.9	0.277	1.9	95.8
8	8.6	0.301	2.6	104.4
9	6.9	0.324	2.2	111.3
10	4.9	0.342	1.7	116.2
11	3.4	0.354	1.2	119.6
12	2.3	0.363	0.8	121.9
13	1.6	0.368	0.6	123.5
14	1.1	0.373	0.4	124.6
15	0.8	0.375	0.3	125.4

Note how the percentage runoff increases through the storm event as the soil moisture content increases and, thereby, give rise to a non-symmetrical net hyetograph. The last column in Table 6.1 shows the soil moisture content at the end of each time step.

6.2.7 Derivation of Δt-hour unit hydrograph

The convolution of the unit hydrograph and the net hyetograph requires the derivation of the Δt = 1 hour unit hydrograph from the IUH through the use of the S-curve method as outlined in §2.4. The IUH and the resulting 1-hour UH are shown in Figure 6.2

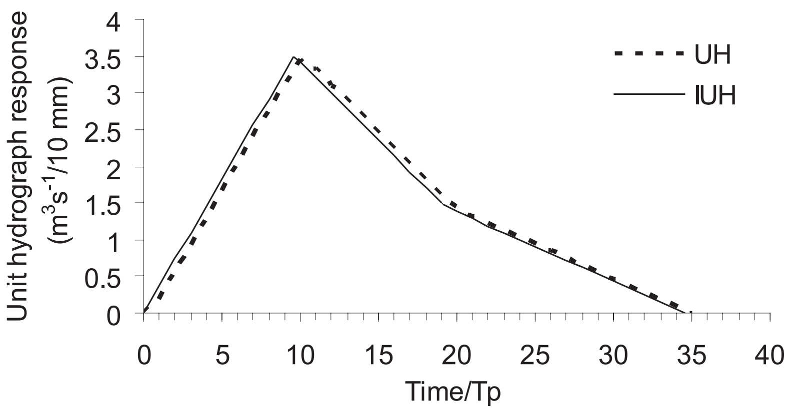


Figure 6.2 *IUH and associated 1-hour UH derived using S-curve technique.*

6.2.8 Derivation of rapid response runoff hydrograph

The convolution of the Δt = 1-hour unit hydrograph and the net rainfall hyetograph from §5.2.6 is carried out through Equation 2.9 and the results shown in Table 6.2.

6.2.9 Calculation of baseflow hydrograph

To calculate the baseflow hydrograph, the ReFH model requires an estimate of initial baseflow, i.e. the flow in the river before the flood event, and the direct runoff hydrograph. Initial baseflow is estimated for the winter season through Equation 4.9

$$BF_0 = (63.8 \times (90 - 120.8) + 5.54 \times 666)\, 10^{-5} \times 186.52$$

$$BF_0 = 3.2 \text{ m}^3\text{s}^{-1}$$

The baseflow hydrograph can be derived by using Equation 2.14 as shown in Table 6.2.

6.2.10 Derivation of total runoff hydrograph

The total runoff hydrograph is obtained by adding the baseflow hydrograph to the direct runoff hydrograph as shown in Table 6.2. The 100-year design flood hydrograph for the River Salwarpe at is shown in Figure 6.3 with an estimated peak flow value of 50.9 m^3s^{-1}.

Table 6.2 *100-year design flood hydrograph for Salwarpe at Harford Hill*

Interval	Total rainfall mm	Net rainfall mm	Direct runoff $m^3 s^{-1}$	Baseflow $m^3 s^{-1}$	Total flow $m^3 s^{-1}$
1	0.8	0.2	0.0	3.2	3.2
2	1.1	0.3	0.0	3.1	3.1
3	1.6	0.4	0.1	3.0	3.1
4	2.3	0.6	0.4	2.9	3.2
5	3.4	0.8	0.8	2.8	3.5
6	4.9	1.3	1.4	2.7	4.1
7	6.9	1.9	2.5	2.6	5.1
8	8.6	2.6	4.1	2.6	6.7
9	6.9	2.2	6.5	2.6	9.2
10	4.9	1.7	9.9	2.7	12.6
11	3.4	1.2	13.9	2.8	16.7
12	2.3	0.8	18.4	3.0	21.5
13	1.6	0.6	23.1	3.3	26.5
14	1.1	0.4	27.9	3.7	31.6
15	0.8	0.3	32.5	4.2	36.7
16			36.8	4.7	41.5
17			40.4	5.3	45.7
18			42.8	6.0	48.8
19			43.9	6.6	50.5
20			43.7	7.2	50.9
21			42.4	7.8	50.3
22			40.5	8.4	48.9
23			38.1	8.9	46.9
24			35.4	9.3	44.6
25			32.5	9.6	42.1
26			29.6	9.9	39.4
27			26.8	10.1	36.8
28			24.3	10.2	34.5
29			22.1	10.3	32.3
30			20.1	10.3	30.4
31			18.3	10.3	28.6
32			16.6	10.3	26.9
33			15.0	10.2	25.3
34			13.5	10.1	23.6
35			12.0	10.0	22.1
36			10.6	9.9	20.5
37			9.2	9.7	18.9
38			7.8	9.5	17.3
39			6.4	9.3	15.7
40			5.1	9.1	14.1
41			3.8	8.8	12.7
42			2.7	8.6	11.3
43			1.8	8.3	10.1
44			1.2	8.0	9.2
45			0.7	7.7	8.4
46			0.4	7.5	7.9
47			0.2	7.2	7.4
48			0.1	6.9	7.0
49			0.0	6.7	6.7

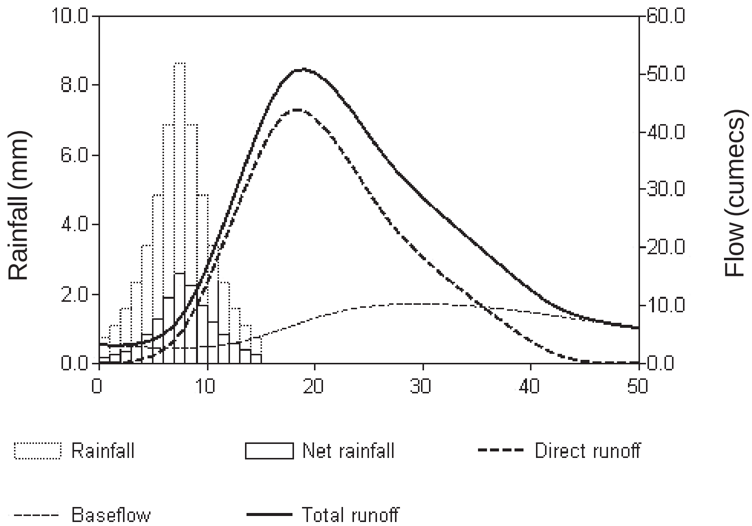


Figure 6.3 *100-year design flood hydrograph for Salwarpe at Harford Mill*

6.3 Simulation of a notable event

Catchment: Gifford Water at Lennoxlove (20007) – as shown in Figure 6.4
Event: 26 April 2000

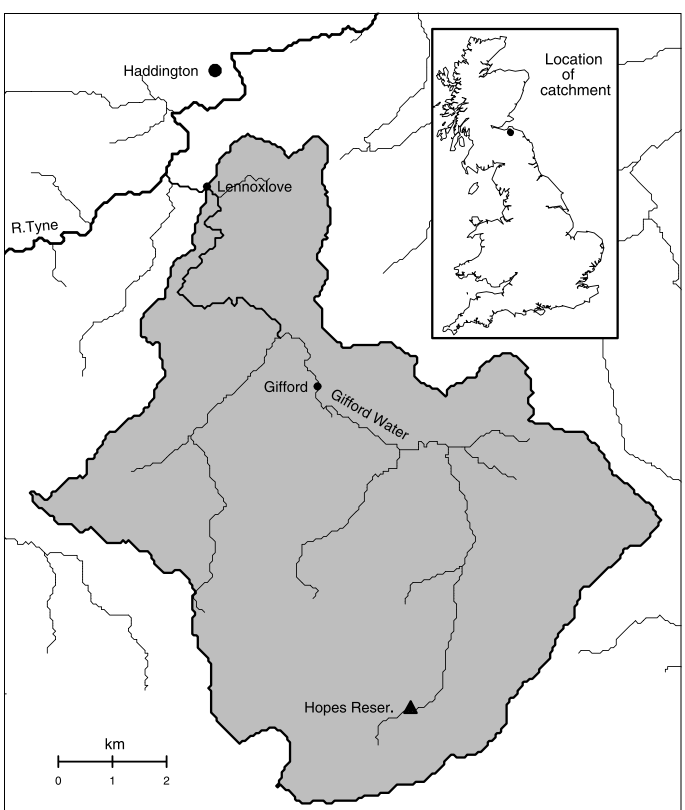


Figure 6.4 *Gifford Water at Lennoxlove (20007)*

Relevant catchment descriptors exported from the FEH CD-ROM v1.0:
AREA = 67.71 km^2, *PROPWET* = 0.43, *BFIHOST* = 0.527

On 26 April 2000 at 7 p.m., a peak flow of 36.6 m^{3}s^{-1} was recorded at this gauging station. The event rainfall and resulting observed runoff are shown in Figure 6.5.

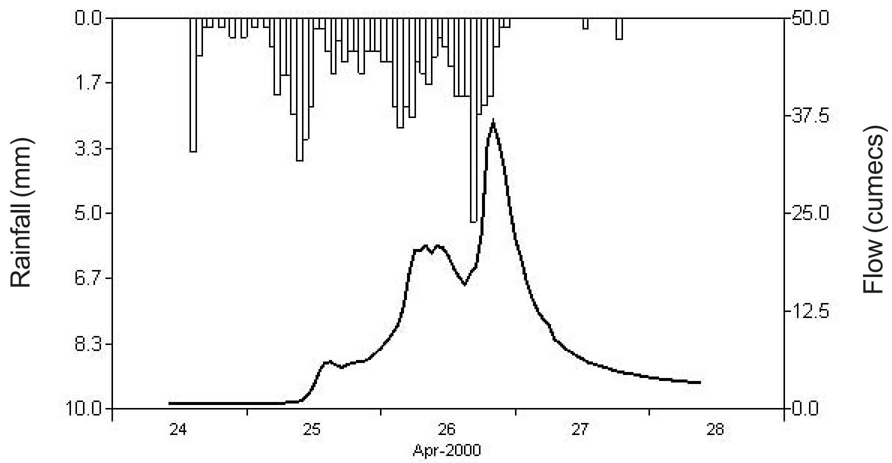


Figure 6.5 *Observed rainfall and runoff for flood event with peak flow on 26 April 2000 at 7 p.m.*

Before simulating the flood event, it is necessary to estimate the four ReFH model parameters. As outlined in Chapter 3, the parameters can be estimated either from direct analysis of observed flood events (§3.2) or through the use of catchment descriptors (§3.3). In this example, observed flood events are available.

6.3.1 Data availability

A total of 13 flood events (including the event of interest, 26 April 2000) have been extracted from hourly time series of runoff and catchment average rainfall and are listed in Table 6.3

Table 6.3 *Available flood events*

Event	Peak flow m^{3}s^{-1}	BF_0 m^{3}s^{-1}	Event	Peak flow m^{3}s^{-1}	BF_0 m^{3}s^{-1}
23-Jan-1993	7.8	1.54	01-Jul-1997	17.8	2.23
14-May-1993	14.6	0.52	17-Oct-1998	7.8	0.71
06-Oct-1993	22.3	0.71	03-Nov-1998	27.9	0.98
13-Dec-1993	11.7	1.76	13-Nov-1998	21.2	1.05
06-Jan-1994	21.1	1.90	25-Jan-1999	7.9	0.88
29-Feb-1994	11.5	0.65	12-Dec-1999	11.0	0.95
			26-Apr-2000	36.6	0.71

The median annual flood (QMED) for this particular catchment is reported by in Volume 3 of the FEH (Institute of Hydrology, 1999) to be 15.3 m^{3}s^{-1}, i.e. four of the events have peak flow values exceeding QMED, increasing the confidence in the performance of the ReFH model for relatively large events. Only the first 12 events will be used to estimate the ReFH model parameters. For each event the initial baseflow (BF_0) has been defined as the first runoff ordinate.

6.3.2 Baseflow parameters (*BL* and *BR*)

The two baseflow parameters *BL* and *BR* are estimated as described in §3.2.3. Of the 12 events, only four were considered to have recession curves sufficiently long and undisturbed for estimation of the baseflow parameters. The fitted baseflow models for the four events are shown in Figure 6.6.

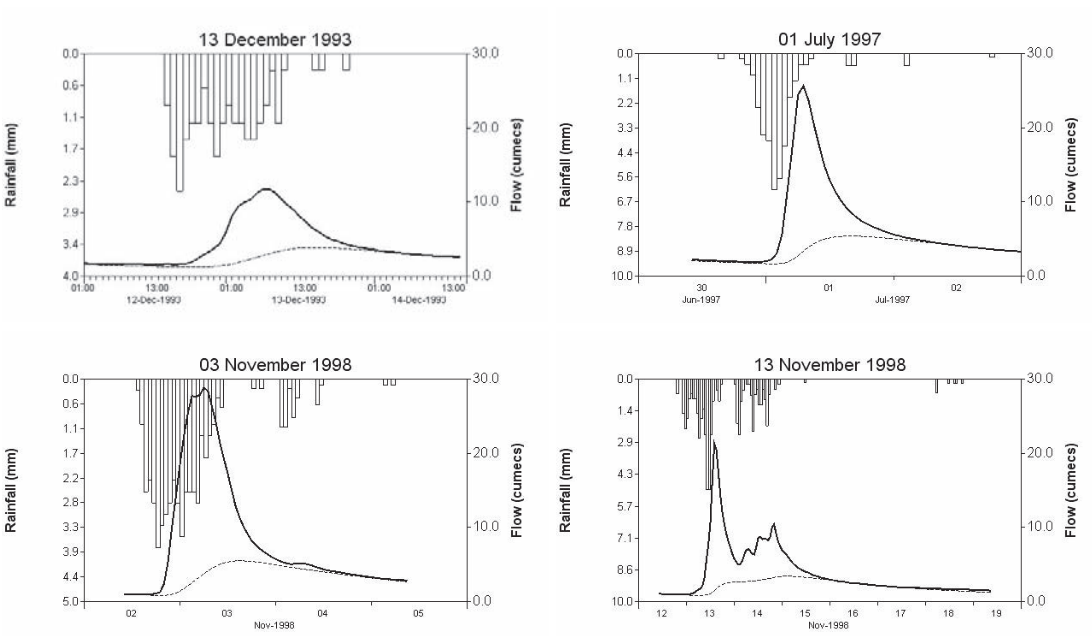


Figure 6.6 *Fitted baseflow models for four events*

A final set of baseflow parameters for the catchment is obtained as the average of the parameters obtained for each event as shown in Table 6.4

Table 6.4 *Baseflow parameters for individual events and mean values*

Event	BL *hours*	BR
13-Dec-1993	46.6	1.60
01-Jul-1997	55.9	1.67
03-Nov-1998	49.6	0.94
13-Nov-1998	88.1	1.27
Average	60.0	1.37

The average baseflow parameters will be used to model all events in the calibration procedure, including the four events used for estimating the average parameters.

6.3.3 Loss and routing model parameters (C_{max} and Tp)

Having reviewed the observed data, estimated the baseflow parameters and defined the initial baseflow value for each event, the remaining two parameters C_{max} and Tp can be estimated using the calibration procedure outlined in §3.2.4. The calibration procedure will select the set of parameter values (C_{max}, Tp) resulting in the minimum mean squared error (MSE) between observed and simulated runoff, see Equation 3.8, summed up over the 12 events included in the procedure. The summed squared difference between observed and simulated runoff for each event is shown in Table 6.5 and a graphical comparison between observed and simulated runoff for each event is shown in Figure 6.7.

Table 6.5 Squared difference between observed and simulated runoff

Event	MSE_i	Event	MSE_i
23-Jan-1993	24.5	01-Jul-1997	940.8
14-May-1993	953.0	17-Oct-1998	113.3
06-Oct-1993	2049.6	03-Nov-1998	1000.0
13-Dec-1993	182.1	13-Nov-1998	287.8
06-Jan-1994	450.3	25-Jan-1999	120.4
29-Feb-1994	106.4	12-Dec-1999	80.5
		Total	6310.6

For each event the soil moisture content at the start of the flood event is modelled as outlined in §3.2.5 using daily catchment average rainfall and evaporation. In addition, the rainfall volume falling between 09:00 a.m. on the day the selected flood event occurred and the actual start of the flood event (see Figure 3.7). Catchment average daily rainfall and evaporation have been estimated using the procedure outlined in §3.2.2 and Equation 3.1, respectively. For each event the start value of soil moisture content when modelling the antecedent soil moisture has been defined as the field capacity FC = 66.2 mm as estimated from Equation 3.10 and the average daily evaporation is estimated from MORECS data to be 550 mm year^{-1} equal to 1.5 mm day^{-1}.

From the calibration procedure, the two parameters C_{max} and Tp are estimated to be C_{max} = 468 mm and Tp = 4.23 hours, respectively. It should be noted that the optimisation procedure does not normalise the individual events to a common scale before the optimisation. Therefore, the largest and longest events will dominate the objective function in Equation 3.8. If one particular event is considered to be too dominant in the optimisation procedure it could be removed and the calibration procedure re-run. For the present example, the event on 6 October 1993 is a relatively large and long event and, as is evident from Table 6.5 and Figure 6.8, is responsible for 32% of the total objective function at the optimal solution. Removing this event will reduce the objective function from MSE = 6310.6 to MSE = 2806.2 and change the optimal solution to C_{max} = 365 mm and Tp = 4.28 hours. While in this case the Tp parameter appears robust, the change to C_{max} is more significant. However a change in percentage runoff of 10% estimated from observed flood event data is not unlikely and lies within the expected uncertainty range.

6.3.4 Simulation of notable event

Having estimated the four ReFH parameters (C_{max}, Tp, BL and BR), the flood event that occurred on the 26-April-2000 can now be simulated. The event is defined as having started at

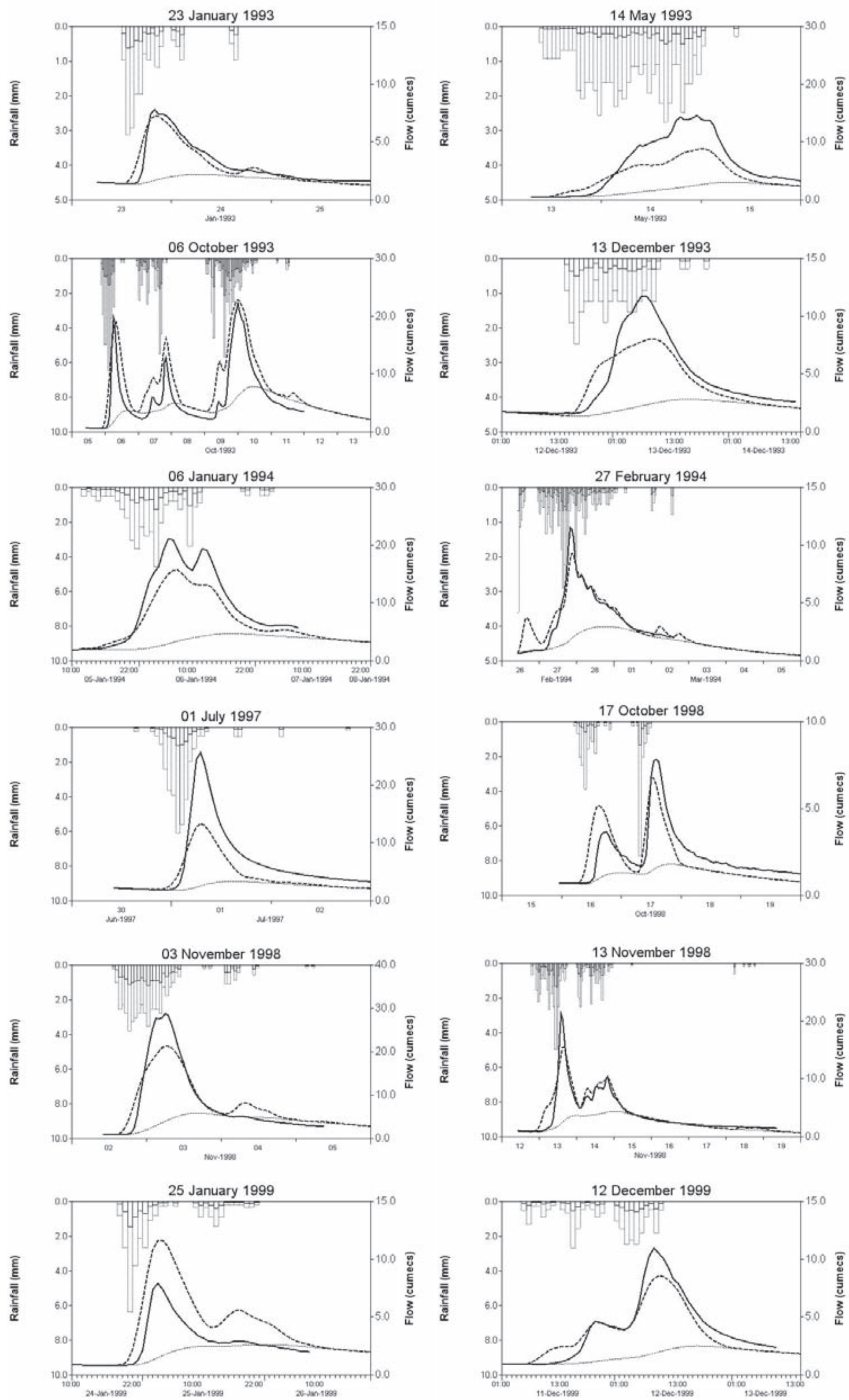


Figure 6.7 *Observed and simulated hydrographs for the 12 calibration flood events*

09:00 a.m. on 24 April 2000. The first rainfall was recorded at 02:00 pm on 24 April and the peak flow occurred at 07:00 p.m. on 26 April. The end of the event is defined at 08:00 a.m. on 28 April.

6.3.5 Derivation of net event hyetograph

First, the loss model is applied to derive the net rainfall hyetograph from the observed rainfall hyetograph. The loss model described in §2.3 requires an estimate of the initial soil moisture content (C_{ini}), which is estimated from catchment average daily rainfall and evaporation for the period 1 January 1999 up to 09:00 a.m. on 26 April 2000. As for the calibration events, a daily evaporation rate of 1.5 mm day^{-1} is assumed and the start value of the soil moisture content in the modelling of antecedent soil moisture was set to FC = 66.2 mm. The daily climate data and the resulting development of the soil moisture content are shown in Figure 6.8.

Through recursive use of Equation 2.1, the percentage (q_t/P_t) for each hourly rainfall value can be derived and the net rainfall obtained for each time step as the total rainfall multiplied with the ratio. The total net rainfall volume is 22.1 mm compared to the total observed rainfall volume of 73.7 mm, i.e. 30% of the total rainfall is transformed into direct runoff.

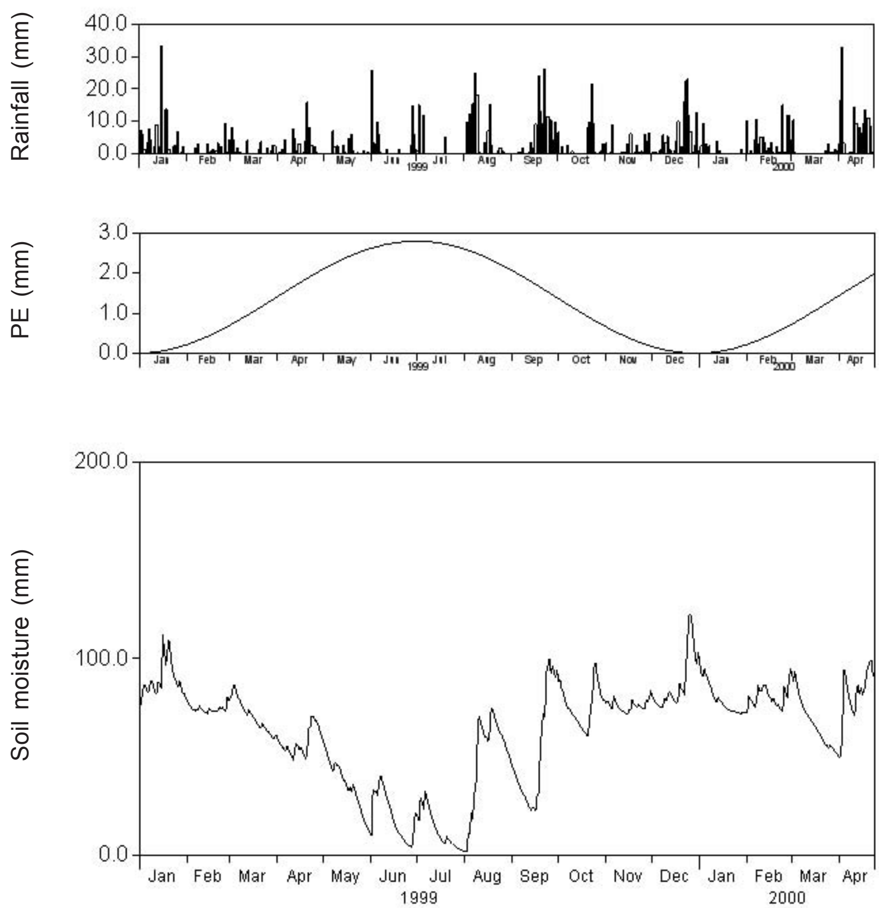


***Figure 6.8** Antecedent rainfall, evaporation and the resulting soil moisture content for the period 1 January 1999 to 09:00 a.m. 26 April 2000*

6.3.6 Derivation of direct runoff hydrograph

Next, the net rainfall hyetograph is transformed into runoff and routed to the catchment outlet using the routing model as described in §2.4. The standard ReFH IUH is adopted and transformed into the appropriate 1 hour UH using the S-curve method as described in as defined in §2.4. The convolution of the 1 hour UH and the net rainfall hyetograph is carried out through Equation 2.9.

6.3.7 Calculation of baseflow hydrograph

The contribution from the baseflow is derived through Equation 2.18. An estimate of the initial baseflow is required, which is defined as the first flow ordinate in the observed event, i.e. $BF_0 = 0.71\ \mathrm{m^3s^{-1}}$. Alternatively, when no observed flow is available the initial baseflow can be estimated from Equation 4.9.

6.3.8 Derivation of total runoff hydrograph

Finally, the total simulated runoff hydrograph is obtained by adding the baseflow hydrograph to the direct runoff hydrograph. A comparison between the simulated and observed runoff hydrographs is shown in Figure 6.9.

In general, Figure 6.9 shows a reasonable agreement between the observed and simulated hydrographs though some underestimation of the largest peak is evident. However, it should be noted that this particular event is a complicated multi-peak event. It is likely that the ReFH model would have performed better on a simpler event.

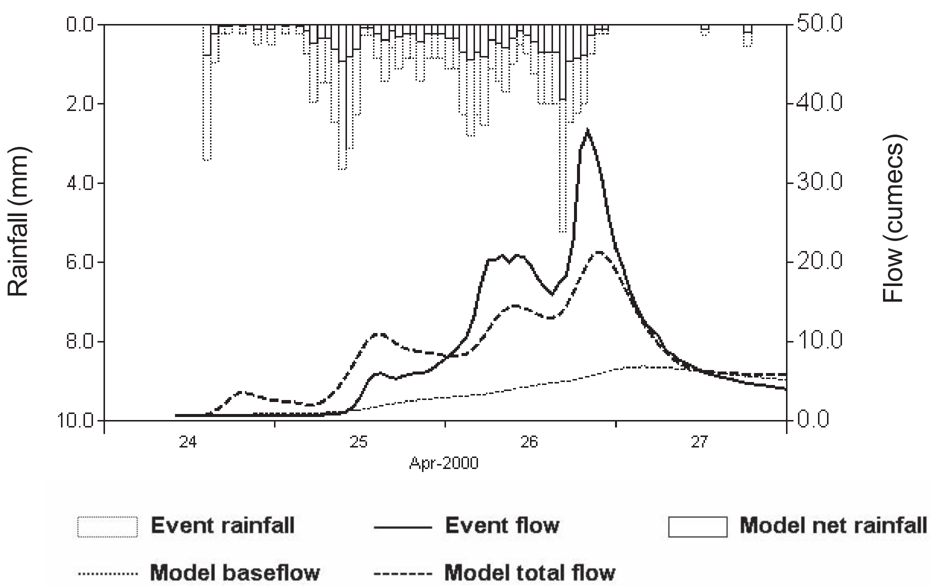


Figure 6.9 *Observed and simulated hydrographs for the event starting 09:00 a.m. on 24 April 2000*

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Appendix A The ReFH loss model

A.1 Introduction

This appendix provides the background to the development of the ReFH loss model and explains how it relates to the FSR/FEH loss model.

A.2 The FSR/FEH loss model

The loss model used in the original FSR/FEH comprises a linear regression model fitted to estimates of percentage runoff obtained from an analysis of observed events. In the FSR, initial calculations of effective rainfall for the observed events were based on a loss rate concept using the Catchment Wetness Index (*CWI*). In the unit hydrograph derivations, *CWI* was used as an arbitrary factor to allow for variation in rainfall losses (loss-rate or percentage runoff) during a storm as

$$LOSS_t = \frac{K}{CWI_t} \tag{A.1}$$

where K is a factor determined for each event to equate the volumes of effective rainfall and quick response runoff. Later, a percentage runoff approach to losses was adopted, where

$$PR_t = K\ CWI_t \tag{A.2}$$

as it was found to perform better than the loss rate method. Based on these findings, *CWI* at the start of the storm was subsequently included in the regression equation for overall (event) percentage runoff. Equations (A.1) and (A.2) essentially define linear relationships between loss rate or Percentage Runoff and soil moisture content. This was later developed into the loss model found in the FEH rainfall-runoff method (Houghton-Carr, 1999) where the losses depend on *CWI*, *SPRHOST*, *URBEXT* and total rain depth P.

A.3 The ReFH loss model

Because of the arbitrary nature of *CWI*, and the fact that the original estimated soil moisture deficit (SMD, or ESMD) calculations are no longer carried out by the Met Office, The ReFH model has instead adopted the uniform Probability Distributed Model (PDM: Moore, 1985) for deriving losses. The PDM model adopted in the ReFH model assumes values of soil moisture capacity C is uniformly distributed over the catchment between 0 and C_{max}. Thus, arranging the soil capacities in size order they would form a triangle as shown in Figure 2.2. Assuming an initial distribution of soil moisture such that all areas less than C_{ini} are saturated, and other areas have a soil moisture deficit ($C - C_{ini}$), then rainfall P will runoff from the saturated areas and increase the content elsewhere to ($C - C_{ini} + P$).
Using Figure 2.2 (§2.2) it can be deduced from geometric considerations that the soil moisture volume (SM) in the catchment can be expressed in terms of the maximum PDM soil moisture capacity as

$$SM = \frac{1}{2} C_{\max} \tag{A.3}$$

Initially, the proportion of the catchment unsaturated is $(C_{max} - C_{ini}) \,/\, C_{max}$, and the initial mean actual moisture content, m_{ini}, is defined by the total capacity less the unsaturated volume

$$m_{ini} = \frac{1}{2}C_{\max} - \frac{1}{2}\frac{\left(C_{\max} - C_{ini}\right)^2}{C_{\max}} \tag{A.4}$$

Note here the difference between m and C, where m is the volume of soil moisture and C denotes the depth of soil moisture as modelled by the PDM in Figure 2.2. Rainfall P increases the initial moisture depth ($C_{t+1} = C_t + P_t$) and from Equation A.4, the change in mean soil moisture volume is

$$m_t - m_{ini} = \frac{\left[\left(C_{\max} - C_{ini}\right)^2 - \left(C_{\max} - C_t\right)\right]}{2C_{\max}} \tag{A.5}$$

which, substituting (C_{ini} + P) for C_t and rearranging, gives

$$m_t - m_{ini} = P_t - \frac{P_t}{C_{\max}}\left(C_{ini} + \frac{P_t}{2}\right) \tag{A.6}$$

Considering that runoff is rainfall minus change in soil moisture (neglecting losses due to evaporation during the flood event), the percentage runoff can be expressed from Equation A.6 as

$$\frac{q}{P} = \frac{C_{ini}}{C_{\max}} + \frac{P}{2C_{\max}} \tag{A.7}$$

where q is runoff and q/P represent percentage runoff. Noting the primary role of the term (C_{ini}/C_{max}) in defining the catchment average percentage runoff, the term $1 - C_{ini}/C_{max}$ therefore represents, approximately, the catchment average fraction of rainfall that infiltrates the PDM soil and, from Equation A.4, that

$$\left(1 - \frac{C_{ini}}{C_{\max}}\right) = \left(1 - \frac{m_{ini}}{SM}\right)^{\frac{1}{2}} \tag{A.8}$$

Equation A.8 is used for estimating the infiltration when modelling antecedent soil moisture condition in §3.2.6.

In terms of effective rainfall separation, the uniform PDM gives generally similar results to the CWI model in Equation A.2, with *CWI* replaced by C_{ini} and the factor K by C_{max}. However, the PDM parameters C_{ini} and C_{max} have clear physical interpretations as state variables (soil moisture content), and a soil characteristic (maximum soil moisture depth) forming a link between runoff response and soil type. The similarity in the ratio of the coefficients of C_{ini} and P in Equation A.7 compared with the corresponding terms 0.22 *CWI* and 0.1 P in the original FSR equation for *PR* (= 100 q/P) (FSR, Vol. I, Equation 6.37) may also be noted, implying a C_{max} value of about 500 mm. This value is generally higher than the observed values of C_{max}, but the comparison ignores the effect of the SOIL term in the FSR loss equation, and the notional maximum deficit of 125 mm in *CWI* refers to deficit from field capacity (drained soil) rather than total capacity. Overall the uniform PDM provides a suitable replacement for the obsolete *CWI* model.

Appendix B Antecedent soil moisture

B.1 Introduction

To obtain an estimate of the soil moisture at the onset of an event, C_{ini}, a continuous soil moisture simulation model was applied using daily input data. The following section contains a description of the analytical background of the model and how it was applied in practice, including how input data were obtained.

B.2 The soil moisture model

The starting point is a simple differential equation, where soil moisture, m, is modelled as a balance between infiltration, f, soil drainage, d, and evaporation, E, using the following equation:

$$\frac{dm}{dt} = f - d - E \tag{B.1}$$

This differential equation is developed for three soil moisture zones:

- upper zone, above field capacity FC, where drainage q depends on moisture content above FC ($d=k(m-FC)$), and evaporation is at the potential rate ($E=p$);
- mid zone, between field capacity FC and rooting depth RD, where drainage ceases but evaporation stays at the potential rate ($E=p$);
- lower zone, below rooting depth RD, where actual evaporation drops linearly with moisture content ($E=p.m/RD$).

For the linear PDM, referring to Figure 3.3 (repeated below), and using the rules of similar triangles, it can be seen that the proportion of any incremental rainfall that runs off is C/C_{max}, and thus the proportion of rainfall that infiltrates is $1 - C/C_{max}$. Note here the difference between m and c, where m is the volume of soil moisture and c is the depth of soil moisture as modelled by the PDM in Figure 3.3. Also from the figure, mean soil moisture m may be found as the difference between the mean soil capacity SM equal to ½ C_{max} and the mean deficit equal to $(C_{max} - c)^2/2C_{max}$. Thus:

$$\frac{m}{SM} = \frac{C_{\max}/2 - (C_{\max} - c)^2/2C_{\max}}{C_{\max}/2} \quad \text{or} \quad 1 - \frac{m}{SM} = \left(1 - \frac{c}{C_{\max}}\right)^2 \tag{B.2}$$

Consequently, the infiltration into a uniform PDM can be written as $i\,(1 - m/SM)^{0.5}$, where i is the rainfall intensity. Thus, for the upper zone (moisture content above field capacity), the soil moisture Equation B.1 becomes:

$$\frac{dm}{dt} = i\left(1 - \frac{m}{SM}\right)^{1/2} - k(m - FC) - p \tag{B.3}$$

The mid zone equation can be obtained by setting k and FC to zero, and the lower zone equation can be obtained by setting FC and p to zero, and treating the $k.m$ term as the actual evaporation loss $p.m/RD$. A simple exact solution of the Equation B.3 does not exist, but a finite difference solution can be found as:

$$\frac{(m_t - m_0)}{t} = i\left(1 - \frac{(m_t + m_0)}{2\,SM}\right)^{1/2} - k\left(\frac{(m_t + m_0)}{2} - FC\right) - p \tag{B.4}$$

Rearranging to isolate the infiltration term:

$$i.t\left(1-\frac{(m_t+m_0)}{2\,SM}\right)^{\frac{1}{2}}=(m_t-m_0)+k.t\left(\frac{(m_t+m_0)}{2}-FC\right)+p.t \tag{B.5}$$

then squaring both sides and dividing through by SM^2 gives:

$$\left(\frac{i.t}{SM}\right)^2\left(1-\frac{m_t+m_0}{2SM}\right)=\left(\frac{m_t}{SM}\left(1+\frac{k.t}{2}\right)-\frac{m_0}{SM}\left(1-\frac{k.t}{2}\right)+\frac{(p.t-k.t.FC)}{SM}\right)^2 \tag{B.6}$$

Now substituting $M=(m/SM)$, $i_*=(i.t\,/\,2SM)$, $E=(p.t-k.t.FC)/SM$, and $k_*=(1+k.t/2)$ gives:

$$\left(\frac{2i_*}{k_*}\right)^2\left(1-\frac{(M_t+M_0)}{2}\right)=\left(M_t-M_0\frac{2-k_*}{k_*}+\frac{E}{k_*}\right)^{\frac{1}{2}} \tag{B.7}$$

and further substituting $G=(M_0(2-k_*)/k_*-E/k_*)$, expanding and collecting terms in M_t and M_t^2 gives the quadratic equation:

$$M_t^2-M_t\left(2G-\frac{1}{2}\left(\frac{2i_*}{k_*}\right)^2\right)+\left(G^2-\left(\frac{2i_*}{k_*}\right)^2\left(1-\frac{M_0}{2}\right)\right) \tag{B.8}$$

with the solution:

$$M_t=\left(G-\left(\frac{i_*}{k_*}\right)^2\right)+\left[\left(G-\left(\frac{i_*}{k_*}\right)^2\right)^2-\left(G^2-\left(\frac{2i_*}{k_*}\right)^2\right)\left(1-\frac{M_0}{2}\right)\right]^{\frac{1}{2}}$$

$$=\left(G-\left(\frac{i_*}{k_*}\right)^2\right)+\frac{i_*}{k_*}\left[-2G+\left(\frac{i_*}{k_*}\right)^2+4\left(1-\frac{M_0}{2}\right)\right]^{\frac{1}{2}} \tag{B.10}$$

Finally re-substituting $(M_0(2-k_*)\,/\,k_*-E/k_*)$ for G and m/SM for M gives soil moisture at the end of a time step, based on rainfall, drainage and evaporation during the time step:

$$\frac{m_t}{SM}=\frac{m_0}{SM}\left(\frac{2}{k_*}-1\right)-\frac{E}{k_*}-\left(\frac{i_*}{k_*}\right)^2+\frac{i_*}{k_*}\left[\left(\frac{i_*}{k_*}\right)^2+\frac{4}{k_*}\left(k_*-\frac{m_0}{SM}+\frac{E}{2}\right)\right]^{\frac{1}{2}} \tag{B.11}$$

where $E=(p.t-k.t.\,FC)/SM$, $k_*=1+k.t/2$, and $i_*=i.t/(2SM)$

Making the substitutions discussed earlier, a similar expression can be found for the mid zone ($FC > m > RD$):

$$\frac{m_t}{SM}=\frac{m_0}{SM}-E-i_*^2+i_*\left[i_*^2+4\left(1-\frac{m_0}{SM}+\frac{E}{2}\right)\right]^{\frac{1}{2}} \tag{B.12}$$

where $E=p.t/SM$ and $i_*=i.t/(2SM)$ (B.13)

and for the lower zone ($m < RD$):

$$\frac{m_t}{SM}=\frac{m_0}{SM}\left(\frac{2}{k_*}-1\right)-\left(\frac{i_*}{k_*}\right)^2+\frac{i_*}{k_*}\left[\left(\frac{i_*}{k_*}\right)^2+\frac{4}{k_*}\left(k_*-\frac{m_0}{SM}\right)\right]^{\frac{1}{2}} \tag{B.14}$$

where $k_*=1+p.t/(2RD)$ and $i_*=i.t/(2SM)$

Although these equations look complex, they are broadly comparable to the ESMD calculations that were used (albeit hidden) in the original FSR analysis, and they are easily solved by computer. ReFH solves these equations at a daily time step, assuming soil moisture m is at FC at the start of the year before the event (giving over a year of run-in time). The daily time step is used up to 9 a.m. on the day of the event, and then the equations are solved for a single time step from 9 a.m. to the start time of the event. However, if soil moisture crosses a zone boundary (RD or FC), the time step is split and the corresponding zone equations applied to each part. Finally Equation B.2 is applied to the m value at the start of the storm, converting it into the PDM equivalent initial storage depth C_{ini}.

The model parameters are given above as SM, FC, RD and k. However, to ensure FC lies between SM and RD, ReFH requires that the FC value is entered in millimetres, while SM is entered as a factor (>1) on FC, and RD is entered as a factor (<1) on FC. ReFH also requires that the drainage coefficient k is entered as an equivalent daily decay factor DK, where $DK = \exp(-k.t)$ with t equal to 1 day.

Appendix C ReFH model parameters

Catchment	No. of events	Baseflow BL h	BR	Loss model C_{max} mm	Routing model Tp h	Up	Uk
7001	16	32.56	1.1	335.3	3.77	0.65	0.8
19002	5	16.12	0.9	260.7	5.46	0.65	0.8
19005	11	23.61	1.04	210.1	4.13	0.65	0.8
20001	10	25.00	1.53	476.0	6.24	0.65	0.8
22006	15	65.70	1.04	272.4	8.82	0.65	0.8
22009	21	75.34	1.52	334.6	7.21	0.65	0.8
23002	9	41.80	1.16	217.6	3.42	0.65	0.8
23006	52	37.30	0.79	166.8	2.94	0.65	0.8
23008	5	50.96	0.61	161.0	6.79	0.65	0.8
23010	6	20.70	0.73	192.1	2.38	0.65	0.8
23011	10	28.80	0.41	148.7	2.63	0.65	0.8
24004	13	69.15	1.2	298.1	4.16	0.65	0.8
24005	46	46.54	1.24	362.4	5.36	0.65	0.8
24007	7	46.58	1.43	282.7	3.29	0.65	0.8
25005	15	60.09	1.01	250.3	8.87	0.65	0.8
25006	26	34.10	0.62	188.2	3.49	0.65	0.8
25019	16	81.74	1.20	354.6	3.64	0.65	0.8
27001	11	26.50	1.34	309.9	6.76	0.65	0.8
27026	8	21.00	0.94	357.7	4.19	0.65	0.8
27027	22	38.00	1.11	219.4	5.30	0.65	0.8
27034	10	23.07	0.90	221.4	5.98	0.65	0.8
28008	18	96.10	2.09	467.3	6.94	0.65	0.8
28026	5	74.92	1.00	232.9	18.74	0.65	0.8
28033	7	28.60	2.18	472.4	1.32	0.65	0.8
28039	33	22.70	0.47	320.8	1.52	0.65	0.8
28041	5	14.65	1.01	210.3	1.78	0.65	0.8
28046	29	146.5	4.05	783.5	6.33	0.65	0.8
29004	8	68.70	1.50	507.8	8.07	0.65	0.8
30001	7	81.75	1.81	644.5	13.71	0.65	0.8
30004	34	71.30	1.35	618.3	6.88	0.65	0.8
30017	20	94.70	1.06	637.7	7.36	0.65	0.8
31005	8	82.84	0.94	232.8	24.47	0.65	0.8
31010	7	57.01	0.99	326.2	10.13	0.65	0.8
32002	5	109.68	2.17	671.0	13.73	0.65	0.8
32003	9	62.30	0.84	248.8	7.05	0.65	0.8
32006	9	70.30	1.89	648.3	8.54	0.65	0.8
34003	9	100.72	3.05	1356.5	11.25	0.65	0.8
34007	5	39.34	0.83	248.1	14.70	0.65	0.8
35008	10	48.70	0.83	250.1	9.58	0.65	0.8
36010	13	50.10	0.60	256.5	5.76	0.65	0.8
37001	7	57.90	0.94	243.9	20.52	0.65	0.8
37003	5	56.20	0.94	412.5	14.79	0.65	0.8
38020	19	41.20	0.57	225.2	5.82	0.65	0.8
39005	15	15.05	1.00	314.9	2.10	0.65	0.8

Catchment	No. of events	Baseflow BL h	BR	Loss model C_{max} mm	Routing model Tp h	Up	Uk
39007	13	58.30	1.95	796.1	11.14	0.65	0.8
39012	8	38.13	1.13	648.5	2.69	0.65	0.8
39017	29	26.73	0.53	321.5	7.06	0.65	0.8
39022	14	70.60	1.36	390.0	13.20	0.65	0.8
39025	13	77.20	2.09	561.6	8.92	0.65	0.8
39052	8	26.33	0.89	408.5	5.41	0.65	0.8
39053	7	34.97	1.07	334.3	5.59	0.65	0.8
39092	6	21.07	0.57	232.5	3.26	0.65	0.8
40005	10	45.50	0.51	232.0	18.87	0.65	0.8
40006	16	33.56	1.15	422.5	3.87	0.65	0.8
40007	10	54.50	0.84	342.8	9.33	0.65	0.8
40008	10	51.79	1.46	493.1	12.95	0.65	0.8
40009	11	34.52	0.83	303.0	5.85	0.65	0.8
40010	24	65.5	0.90	294.3	14.82	0.65	0.8
41005	23	40.92	1.51	400.6	9.93	0.65	0.8
41006	13	22.50	0.54	283.2	5.63	0.65	0.8
41028	14	34.40	0.79	313.7	6.32	0.65	0.8
41801	13	13.24	0.45	261.1	1.32	0.65	0.8
45002	20	66.20	2.35	451.0	5.69	0.65	0.8
45004	14	30.03	0.78	328.2	6.61	0.65	0.8
45011	11	30.76	1.14	339.5	4.19	0.65	0.8
46005	14	13.04	0.49	199.0	2.38	0.65	0.8
52010	9	43.50	1.08	266.0	7.06	0.65	0.8
53005	12	72.29	3.24	759.0	6.11	0.65	0.8
53007	14	40.12	1.36	409.9	7.06	0.65	0.8
53008	10	44.10	1.31	486.3	9.81	0.65	0.8
54004	9	30.86	2.82	555.2	8.25	0.65	0.8
54011	14	26.53	0.54	333.0	9.56	0.65	0.8
54019	15	79.70	1.35	299.3	24.7	0.65	0.8
54034	7	56.30	1.97	398.8	5.13	0.65	0.8
55013	5	86.48	3.29	479.4	6.11	0.65	0.8
55022	8	65.81	0.57	257.6	9.96	0.65	0.8
55026	5	30.80	0.98	254.5	3.76	0.65	0.8
56003	5	56.04	1.91	409.6	2.05	0.65	0.8
56005	12	65.64	1.84	459.0	3.61	0.65	0.8
56006	13	39.80	0.96	334.6	2.26	0.65	0.8
57004	17	47.20	1.31	392.5	5.26	0.65	0.8
57005	16	64.70	2.00	360.5	3.77	0.65	0.8
57006	30	35.20	1.40	321.5	2.26	0.65	0.8
58003	11	29.17	1.31	432.2	4.02	0.65	0.8
58006	15	43.00	0.90	293.4	2.26	0.65	0.8
60002	9	42.90	1.56	340.8	5.75	0.65	0.8
61001	16	53.99	2.33	531.1	4.87	0.65	0.8
61003	5	44.10	0.99	302.2	3.49	0.65	0.8
66011	10	24.40	0.57	292.7	2.65	0.65	0.8
68006	6	14.18	1.08	247.5	3.21	0.65	0.8
69013	6	19.84	1.04	408.7	2.90	0.65	0.8

Catchment	No. of events	Baseflow *BL* *h*	*BR*	Loss model C_{max} *mm*	Routing model *Tp* *h*	*Up*	*Uk*
69027	6	63.02	1.76	282.1	4.89	0.65	0.8
70006	7	52.01	1.63	292.2	2.69	0.65	0.8
72002	14	23.8	0.65	198.1	4.97	0.65	0.8
72006	8	55.88	0.88	166.1	5.08	0.65	0.8
72818	9	58.9	0.83	331.0	5.54	0.65	0.8
73005	11	58.49	1.98	392.1	4.30	0.65	0.8
73008	8	62.86	2.86	463.3	5.53	0.65	0.8
74001	7	21.69	0.91	203.5	2.56	0.65	0.8
77002	7	34.57	0.88	229.7	3.84	0.65	0.8
84008	7	29.03	1.07	244.7	3.20	0.65	0.8

Appendix D Calibration of the ReFH design method

D.1 Introduction

In the context of modelling a flood event using a rainfall-runoff model it is important to distinguish between a flood event resulting from an observed storm (as discussed in §3.2) and a design storm derived by imposing a design storm (depth-duration-profile) on the rainfall-runoff model jointly with specified soil moisture condition. In contrast to an observed flood event where the purpose of the modelling exercise is to resemble the observed hydrograph, a design event is a probabilistic estimate of a flood event whose magnitude is exceeded with a specified frequency (Pilgrim and Cordery, 1993).

A key part of an improved rainfall-runoff method is the development of method that can be generalised to allow the computation of a design flood. The development of a generic design method is a complex procedure based on characterising the joint distribution of a number of different flood-generating mechanisms such as rainfall depth, rainfall duration, rainfall profile and antecedent soil moisture wetness (NERC, 1975). The joint probability problem arises because a specific flood event might be the result of many different combinations of the flood-generating mechanisms, rather than being defined by one particular combination. For example, a flood of a given magnitude might result from a very extreme rainfall event on dry soil, or from a smaller rainfall event on a very wet catchment. It is anticipated that the design model will be applied by a variety of users with different background knowledge and experience in flood hydrology. Furthermore, the method is likely to be an integral part of the decision-making procedure in engineering projects involving substantial social, economic and environmental impacts. It is therefore a key requirement of the hydrological design procedure that it is relatively simple to apply and that the results should be easily reproducible. The ReFH design model has been calibrated to ensure that the design hydrograph of a specified return period is generated from a unique set of design input variables. The calibration is based on the 100 catchments where ReFH model parameters are available.

D.2 Choice of a single set of design inputs

To identify a specific combination of the design input values to be used for simulation of a design flood event, a series of numerical simulation and optimisation experiments were conducted. The principles of this method are described by Pilgrim and Cordery (1993) as values derived from comparison of floods and rains of the same probability. At each catchment where ReFH model parameters are available from analysis of observed events as well as sufficient observed annual maximum (AMAX) events, a flood frequency curve is obtained through pooled analysis of the AMAX events as outlined in Vol. 3 of the FEH (Robson and Reed, 1999). Next, values of the ReFH model design parameters are determined which connect a design rainfall of a specified return period to the resulting design flood event with a peak flow value of a similar return period, as determined from the statistical flood frequency curve.

In practice, the calibration procedure is implemented in the form of a minimisation problem, where, for any given catchment at any given return period T, the difference between the peak flow estimate generated from the ReFH model (using T-year design rainfall) and the corresponding T-year estimate obtained from the pooled analysis (as illustrated in Figure 4.1) is minimised by adjusting the free variable, i.e.

$$\min_{\theta}\left\{\left(\frac{\left(Q_{T,\mathrm{Re}FH}(\theta)-Q_{T,Stat}\right)^2}{Q_{T,Stat}}\right)\right\}=\min_{\theta}\left\{d_T^2(\theta)\right\} \qquad \text{(D.1)}$$

where T is the target return period, θ is the calibration parameter and $Q_{T,ReFH}$ and $Q_{T,Stat}$ are the T-year event obtained from the ReFH model and the pooled statistical analysis of AMAX peak flow data, respectively. The minimisation was carried out using a golden section search minimisation procedure (Press *et al.*, 1997).

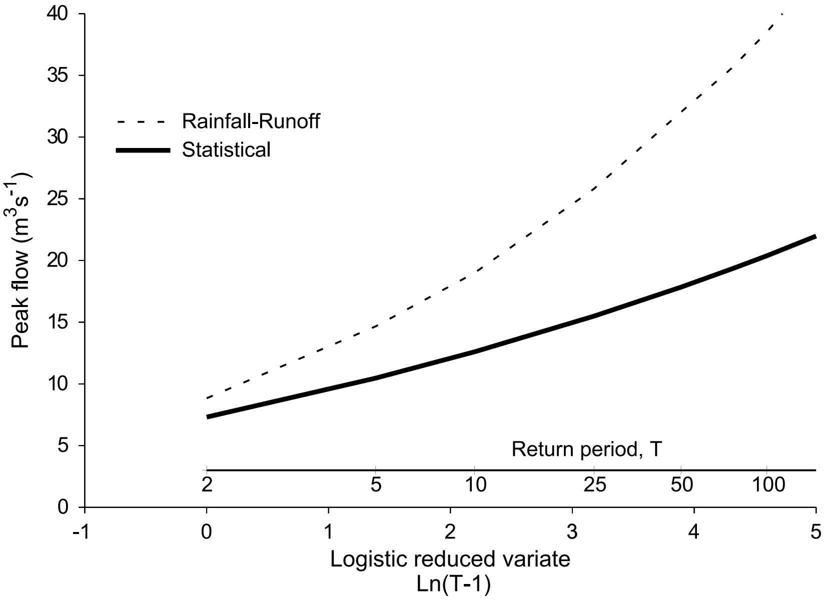


Figure D.1 *Comparison of steepness of growth curves for FEH and FSR design rainfall and pooled statistical flood frequency analysis.*

Selecting which model parameters should be design variables was done with reference to the ReFH model structure and the results were reported in the Flood Studies Report (FSR I, 6.7.3-6) concerning the sensitivity of an event-based rainfall-runoff method to four different design variables: rainfall depth, rainfall duration, rainfall profile and soil moisture content at the start of a flood event. The FSR study concluded that, though important, both rainfall profile and rainfall duration should be kept at catchment specific values in the design method, as the method was found to be less flexible with regard to these variables than to rainfall depth and initial soil moisture content.

Based on the results reported in the FSR (I, 6.7.6) it was decided that the FSR/FEH storm profiles and the definition of the critical storm duration should remain unchanged in the ReFH design method. Furthermore, it was decided, in contrast to the FSR/FEH method, to adopt an equal relationship between return period of design rainfall and the generated design flood, i.e. the 100-year flood is generated by the 100-year rainfall rather than the 140-year rainfall as in the FSR/FEH method (Houghton-Carr, 1999). The adoption of an equal relationship between rainfall and flood hydrograph will bring the method in line with other hydrological design practice for urban areas in the UK. Even though the design storm duration has little impact on the peak flow value, it is an important parameter controlling the runoff volume. The choice made to maintain the FSR/FEH definition of design storm duration in the revitalised FSR/FEH rainfall-runoff method will enable calibration and use of the design method but, as in the FSR/FEH method, no considerations were made with regards to the resulting runoff volumes.

Initial attempts to reconcile the flood frequency curves (FFC) derived by imposing the FEH design rainfall on the ReFH model with the corresponding FFC obtained through FEH statistical method proved problematic. The growth curves of the FEH design rainfall model are generally steeper than the flood growth curves resulting from the FEH statistical method, where the steepness of a growth curve is defined as the ratio between the 100-year and the 5-year growth factors. In Figure 4.2 the steepness of the growth curves derived from both the FEH and the FSR design rainfall models are plotted against the steepness of the flood growth curves derived for 108 catchments. From the figure it is clear that the growth curves of the FEH design rainfall model are steeper, in general, than both the FSR rainfall growth curves and the flood growth curves.

When trying to derive a FFC using the FEH rainfall, the ReFH model must align the output from the ReFH model with the observed FFC derived from statistical analysis, i.e. convert the steep rainfall growth curve into a less steep flood growth curve. This means that the ReFH model must lose increasingly more water at higher return periods than at lower return periods. The extra losses can be imposed on the design method by

- reducing the rainfall depth as return period increases;
- specifying increasingly dry initial soil conditions at higher return periods;
- modifying the ReFH model structure depending on return period.

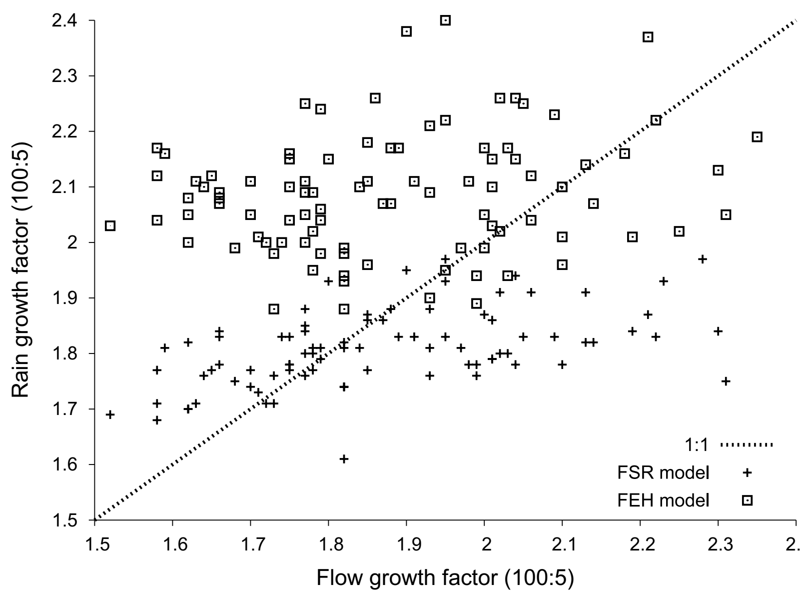


Figure D.2 *Difference between flood frequency curves from pooled statistical method and as computed by the ReFH model. Calibration performed by minimising* d^2 *for each return period.*

The first option for reconciling the two methods was chosen in the development of the FSR method and has subsequently led to much confusion about how to interpret the resulting relationship, i.e. why does the 140-year rainfall event result in a 100-year flood? It was decided not to adopt this option in the ReFH method in order to maintain clarity. The second option, to introduce increasingly dry initial conditions at higher return periods, is somewhat counter-intuitive, especially for winter flooding. Furthermore, the initial baseflow value depends on the initial soil moisture, see Equation 4.9, and increasingly dry soils would lead to a decrease in the baseflow contribution with increasing return period.

The third option, to modify the ReFH model, requires careful consideration as the model in its present form was found to be effective in modelling the observed flood events. Furthermore, few large events are available for justifying any changes at high return periods.

No quantifiable trend was identified concerning the effect of event magnitude on the time to peak (*Tp*) parameter, though evidence seems to suggest a reduction in *Tp* for very large events could be warranted (Kjeldsen *et al.*, 2005). However, introducing this effect in the design model will only compound the identified problem of the difference between the rainfall and flood growth curves.

The ReFH loss model described in §2.2 and in Equation 2.1 is based on the PDM model, which has a proven record in the UK and the only parameter in the loss model is the maximum soil depth (C_{max}), which is considered a physical parameter that should not change with rainfall magnitude. As a compromise between these options it was decided to estimate a catchment specific value of the initial soil moisture condition (C_{ini}) and then introduce a correction factor α_T in the loss model as shown in Equation D.2 below

$$q_t/P_t = \begin{cases} \alpha_T\left(\dfrac{C_{ini}}{C_{\max}}\right)+\dfrac{P_t}{2C_{\max}} & t=1 \\ \left(\dfrac{C_{t-1}}{C_{\max}}\right)+\dfrac{P_t}{2C_{\max}} & t=2,3\ldots \end{cases} \qquad \text{and } C_{t+1} = C_t + P_t \qquad \text{(D.2)}$$

Note the difference between the design model loss model (Equation D.2) and the loss model used when analysing the observed events, Equation 2.1. The factor α_T is used in the calibration procedure as the free variable and will only be used when estimating a design hydrograph. The coefficient does not have a direct physical interpretation and is only a calibration parameter that reflects limitations in the underlying model structure, assumptions and boundary conditions, which should be the focus of future research to improve the method.

Having introduced the α_T coefficient as the free variable it then becomes necessary to determine the design input value of the initial soil moisture (C_{ini}) to complete the design package. By assuming the α_T coefficient to be equal to one for a 5-year return period ($\alpha_T = 1$), the corresponding values of C_{ini} can be derived using the calibration procedure outlined above, i.e. aligning the derived 5-year return period estimates with the statistical estimate of the 5-year return period flood. The resulting estimates of C_{ini} were adopted as the design input values to the ReFH model when generating a design hydrograph of any given return period.

D.3 Seasonality

Allowing for the development of a seasonal design method, considering a summer and a winter season independently, it is necessary to divide the available 100 catchments into two samples depending on whether a particular catchment is summer-critical or winter-critical.

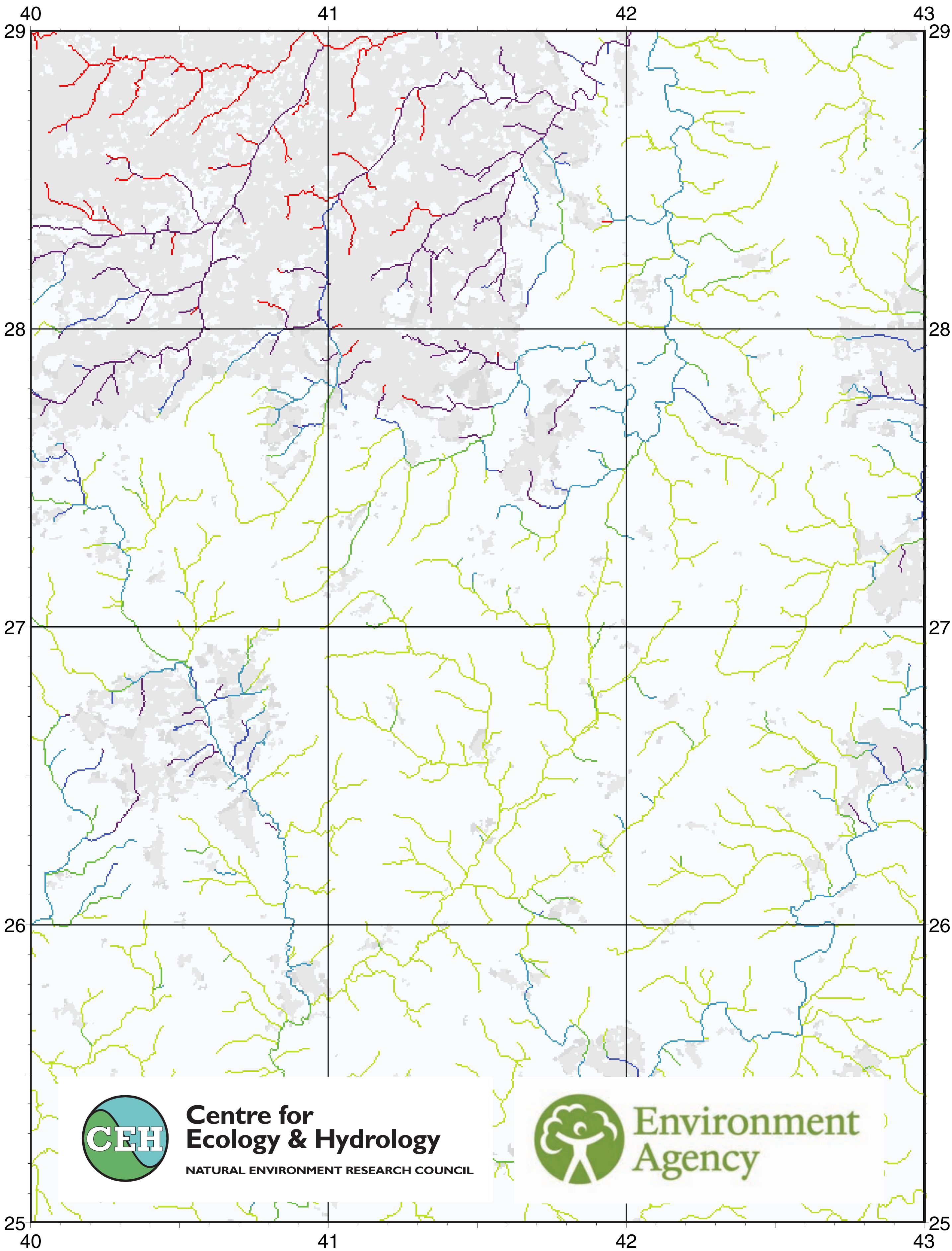
The FSR/FEH method does not explicitly consider flooding in different seasons and the only design input variables with distinct seasonal variation are the design rainfall profile and the rainfall/runoff return period scaling factor. If a catchment is considered rural ($URBEXT_{1990} < 0.125$) then a winter design profile is used but if the catchment is heavily urbanised ($URBEXT_{1990} \geq 0.125$) then the summer design rainfall profile is used and the return period scaling factor is abandoned, i.e. the 100-year design rainfall generates the 100-year flood. The adjustment of the rainfall-runoff return period scaling factor for heavily urbanised catchments was not part of the original FSR method (NERC, 1975) but introduced later (Institute of Hydrology, 1979) to ensure compatibility with design methods used in urban drainage.

The problem of characterising the seasonal flooding pattern of a catchment without access to hydrological data is important, as the design method is anticipated for use mainly at ungauged sites. Unfortunately, there has been limited research in this area, especially with relevance to the design flood issue. One exception is Bayliss and Jones (1993), who tested two different flood seasonality measures for 857 catchments in the UK and related the results to commonly available catchment descriptors. The study showed that the majority of catchments are characterised as flooding in the winter season. Catchments characterised as summer flooding catchments generally had a catchment *AREA* less than 150 km^2 but that *URBEXT* is the dominating factor in defining a summer flooding catchment. This is clearly an issue in need of more research but the definition used in the FSR/FEH method to distinguish between rural and urban catchments was adopted for the revitalised FSR/FEH rainfall-runoff method to separate the available catchments into summer ($URBEXT_{1990} \geq 0.125$) and winter catchment ($URBEXT_{1990} < 0.125$), respectively. Based on this definition the 100 catchments were divided into 93 winter catchments and 7 summer catchments. The ReFH design model will be calibrated independently for the two seasons. The number of summer catchments is clearly a critical factor but is related to the lack of good quality gauged data from small urbanised catchments.

D.4 Pooled frequency analysis

The procedure for conducting pooled flood frequency analysis, as outlined in Vol. 3 of the FEH (Institute of Hydrology, 1999), is time-consuming and preferably requires expert knowledge of the site of interest. In the development of the revitalised FSR/FEH rainfall-runoff method, estimates are required at 100 different catchments. To break down the task to a manageable size, the software developed by Morris (2003) for automatic generation of pooled estimates was used to estimate the parameters of the Generalised Logistic (GLO) distribution for each of the 100 catchments considered. The pooling-group was created for a target return period of 100 years, i.e. each *pooling-group* contains a minimum of 500 AMAX events. The pooled estimates were obtained using AMAX events from the HiFlows-UK dataset provided to CEH in August 2004 by JBA Consulting. No AMAX data could be identified for the gauging station 72818 on the New Mill Brook at Carver's Bridge. As a result this gauging station was not included in the calibration of the design method.

The pooling method outlined in the FEH provides a weighted average of the L-moment ratios of all the AMAX records included in a pooling-group. The pooling-group is formed based on site similarity and considers similarity in terms of *AREA*, *SAAR* and *BFIHOST*. The site similarity approach is limited by the availability of catchments in the database. If a subject site has catchment characteristics that are unusual, compared to the bulk of the catchments in the data base, the pooling method will be forced to include less similar sites in a pooling-group to reach the required number of AMAX events. The database of AMAX events has a limited number of catchments which are very small, very large, very wet ($SAAR > 1500$ mm) or with high *BFIHOST* values ($BFIHOST > 0.7$). This might affect the performance of the pooling-group for catchments with any of these characteristics.



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