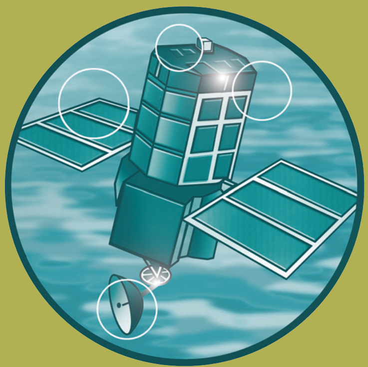
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Revitalisation of the FSR/FEH rainfall runoff method

R&D Technical Report FD1913/TR



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Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Revitalisation of the FSR/FEH rainfall-runoff method

R&D Technical Report FD1913/TR

Produced: July 2005

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Statement of use
This report gives a detailed account of the research undertaken during project FD1913 *Revitalisation of the FSR/FEH rainfall-runoff method* which was funded by the Joint Defra/Environment Agency Flood and Coastal Management R&D Programme. Further information about the application of the new rainfall-runoff method for hydrological design can be found on the FEH website: www.ceh.ac.uk/feh

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Executive Summary

This is the final report for project FD1913 *Revitalisation of the FSR/FEH rainfall-runoff method*. Additional funding was provided by the Scottish Executive to allow the scope of the project to be broadened to include Scotland, and this report includes details of an analysis of 101 catchments in Great Britain. Results specific to the use of the revitalised FSR/FEH rainfall-runoff method in Scotland will be reported separately.

The FSR/FEH rainfall-runoff method is a widely used tool for design flood estimation in the UK. The method was first documented in the Flood Studies Report (FSR) in 1975, and since then numerous studies have updated and improved the method. The latest revision was the technical restatement of the method published in Volume 4 of the Flood Estimation Handbook (FEH) in 1999. Despite these improvements, the basic model structure and the design estimation package have remained unchanged since the first FSR version. The widespread use of the method has prompted valuable feedback from the user community, including critical observations about existing procedures and areas in need of improvement.

The aim of this project was to make improvements to the key components of the FSR/FEH rainfall-runoff method taking advantage of new data, updated analytical techniques and recent advances in computation. The first chapter of the report introduces the objectives of the project and discusses the development of event-based rainfall-runoff modelling for hydrological design in the UK. The motivation for the current study is discussed, in particular the concern that the introduction of the FEH rainfall depth-duration-frequency (DDF) model caused the rainfall-runoff method to overestimate design floods in comparison to the FEH statistical method. The scope of the project is presented and its context within the Flood and Coastal Management R&D Programme is described.

In Chapter 2, the updating of the Flood Event Archive (FEA) is described in detail. The existing archive was reviewed with the co-operation of gauging authorities and others with relevant experience and, where possible, data for more recent flood events were added. Sources of additional flood event data were identified and data for a number of recent flood events of high magnitude were added to the dataset.

Chapter 3 describes the structure of the Revitalised Flood Hydrograph (ReFH) model which has been developed to replace the unit hydrograph and losses model at the core of the FSR/FEH rainfall-runoff method. The ReFH model has three components: a loss model, a routing model and a baseflow model. The loss model uses a soil moisture accounting approach to define the amount of rainfall occurring over the catchment that is converted to direct runoff. The rainfall losses are derived as the event unfolds, rather than being defined by a fixed value of percentage runoff. The routing component of ReFH uses the unit hydrograph concept, adopting a kinked triangle as the standard shape. Finally, the baseflow model is based on the linear reservoir concept with its

characteristic recession defined by an exponential decay controlled by the recession constant termed baseflow lag (BL).

The original formulation of the ReFH model as described above has a total of nine parameters and three boundary conditions. Chapter 4 describes the next stage of the analysis which refined the model structure, reducing the number of parameters and making the model more practical to apply in the design context. A detailed analysis of 14 catchments led to the final model structure defined by four parameters and two initial conditions.The final form of ReFH was applied to 101 catchments in Great Britain using a two-stage optimisation procedure. Examples of the results are given, model performance being evaluated by the comparison of observed and simulated flow hydrographs, and results of an investigation of the relationship between event magnitude and catchment response time are presented.

Chapter 5 introduces the concept of a design package and describes the design inputs required in the new ReFH method. Although the study has retained the use of the FEH depth-duration-frequency model, an analysis of seasonal rainfall frequency for durations of 1 hour and 1 day has been used to develop seasonal correction factors which are applied to the all-year design depth values. The value of the correction factor depends on location, season and rainfall duration. The analysis of areal reduction factors and design rainfall profiles was outside the scope of the project, and the ReFH design method retains the procedures originally presented in the FSR with respect to these concepts.

The calibration of the ReFH design method is described in detail in Chapter 6. Pooled analysis of annual maximum flow data from the HiFlows-UK dataset was used to ensure that the new method would provide results consistent with the existing FEH statistical method of flood frequency estimation. A new feature of the ReFH method is that the T-year flood is generated by the T-year design rainfall event. Chapter 7 describes the development of catchment descriptor equations to enable the ReFH model parameters to be estimated at ungauged sites throughout Great Britain, and details of model testing and validation for both gauged and ungauged sites are given in Chapter 8.

The final conclusions and recommendations are detailed in Chapter 9. Special emphasis is given to the perceived limitations of the methodology in its present state of development and areas where further research is most likely to lead to future improvements are suggested. In particular, further research is needed on the performance of the model in urban catchments, although the availability of suitable rainfall and flow data may be a limiting factor. Further research would also help to improve the understanding and modelling of seasonal flood generating processes in the UK.

Software in the form of an Excel spreadsheet has been developed to allow implementation of the ReFH design method. This can be downloaded free of charge from the FEH webpage:

www.ceh.ac.uk/feh

Contents

List of figures

List of tables

Glossary

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
HOST	Hydrology of Soil Types (soil classification)
IHDTM	Institute of Hydrology Digital Terrain Model
IUH	Instantaneous unit hydrograph
λ_d	Seasonal correction factor for d-hour/day rainfall
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 below 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)
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 (m^3s^{-1} / 10 mm)
UH	Unit hydrograph
U_k	Degree of kink in the standard unit hydrograph
URBEXT	Extend of urban and suburban land cover
Up	Unit hydrograph peak (m^3s^{-1} / 10 mm)
w	Weight
WLS	Weighted least square

1. Introduction

1.1 Background to Project FD1913

This report presents the final results of R&D Project FD1913 *Revitalisation of the FSR/FEH rainfall-runoff method*. This is part of the Fluvial, Estuarine and Coastal Processes Theme of the Joint Defra/Environment Agency Flood and Coastal Management R&D Programme. Part of the way through the project, additional funding was received from the Scottish Executive to increase its scope to include the consideration of catchments in Scotland. Although data from several Scottish catchments have been used in the project, details of a more comprehensive analysis of Scottish catchments will be reported separately.

Although the FSR/FEH rainfall-runoff method was originally conceived as part of the analysis described in 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) (IH, 1999) came the introduction of new design inputs to the method, although the form of the underlying model remained largely unchanged.

Users of the rainfall-runoff method have made some 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. The objectives of this study were to make 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 study has focused on improving the hydrological process description underpinning the rainfall-runoff method and the inclusion of recent and relatively large flood events into the development of the design method.

1.2 Development of event-based rainfall-runoff models

Rainfall-runoff modelling techniques for the estimation of design floods 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. Figure 1.1 illustrates this evolution schematically, each point on the time-line representing a significant advance in the development of event-based modelling for hydrological design in the UK.

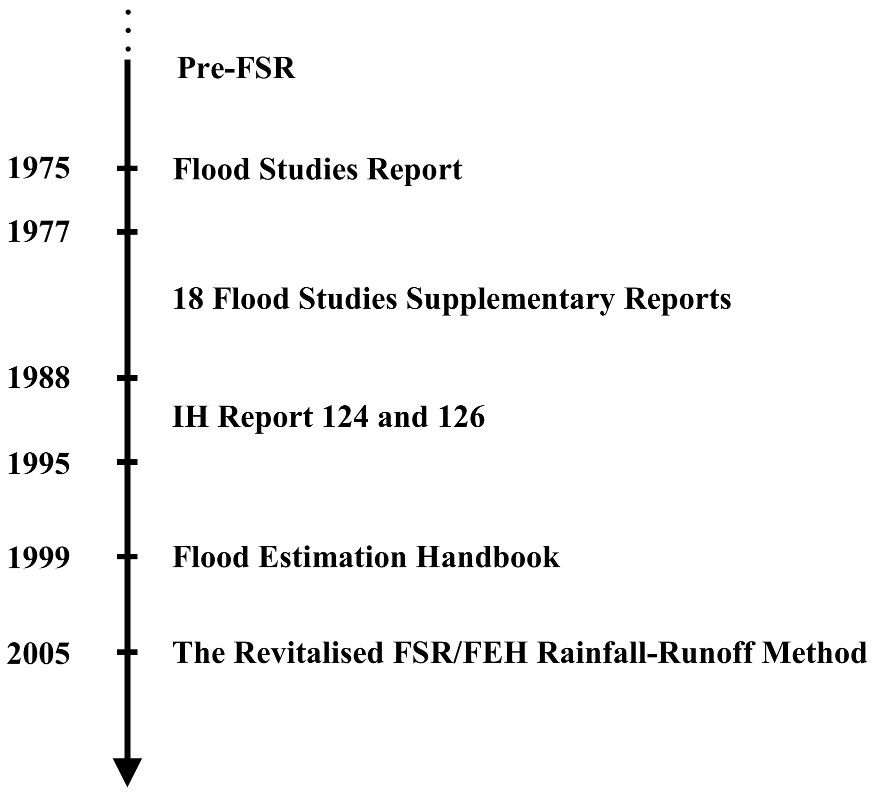


Figure 1.1 Time-line of significant developments of the rainfall-runoff method for design flood estimation in the UK

1.2.1 Pre-FSR

An excellent overview of the state-of-the art of design flood estimation in the period leading up to the publication of the FSR in 1975 is provided by Wolf (1965) who focuses on both theoretical and practical aspects of design flood estimation. Special emphasis is given to the report published by the Institution of Civil Engineers entitled *Floods in Relation to Reservoir Practice* (ICE, 1933) which was updated in 1960 (ICE, 1960) with additional data on floods recorded in the UK between 1933 and 1957. This report formed the foundation of reservoir design in the UK using a normal maximum curve to derive design estimates rather than a probabilistic approach. Another focus of Wolf (1965) is the emergence of the unit hydrograph as a powerful tool for hydrological rainfall-runoff modelling following publication of the original idea by Sherman (1933). The use of unit hydrograph-based modelling techniques and their possible application to ungauged sites was popularised mainly by Nash (1960; 1966). The unit hydrograph was subsequently adopted in the FSR for modelling flood hydrographs.

1.2.2 Flood Studies Report

In 1967, the Committee on Floods of the ICE (ICE, 1967) recommended research into improved techniques for flood estimation, thereby initiating the research programme that ultimately resulted in the publication of the FSR

(NERC, 1975). As well as describing an extensive statistical analysis of gauged flow maxima, the FSR contained procedures for simulating observed floods, T-year design floods and probable maximum floods using a unit hydrograph-based rainfall-runoff model. The unit hydrograph and losses model forms the core of the method. This model, presented in its simplest form, 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 at 143 catchments in the UK. Using multivariate linear regression techniques, the model parameters were linked to mapped catchment characteristics thereby allowing the use of 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. The design model developed in the FSR has formed the core of design flood estimation using rainfall-runoff models up to the present time. The main steps in the method are illustrated in Fig.1.2.

1.2.3 Flood Studies Supplementary Reports

A series of 18 Flood Studies Supplementary Reports (FSSRs) were issued in the period from 1977 to 1988 (Houghton-Carr, 1999). The most important of these with respect to the rainfall-runoff model were FSSR1 (IH, 1977) which investigated the properties of the areal reduction factor in design flood estimation, FSSR16 (IH, 1985) which presented revised model parameter estimation equations and FSSR5 (IH, 1979) considering flood estimation in catchments subject to urbanisation. Also, FSSR13 (IH, 1983) which considered the use of data transfer from nearby gauged catchments (donor/analogue catchments) to facilitate parameter estimation at ungauged sites has been widely adopted in practice.

1.2.4 Institute of Hydrology Reports

From 1988 and until the research for the Flood Estimation Handbook (FEH) commenced in 1995, specific recommendations for national application of the FSR rainfall-runoff model were published as part of the Institute of Hydrology (IH) Report series. In particular, IH Report 124 (Marshall and Bayliss, 1994) contained recommendations on the use of the FSR method on small catchments and IH Report 126 (Boorman *et al.* 1995) presented new parameter estimation equations based on improved soil classification.

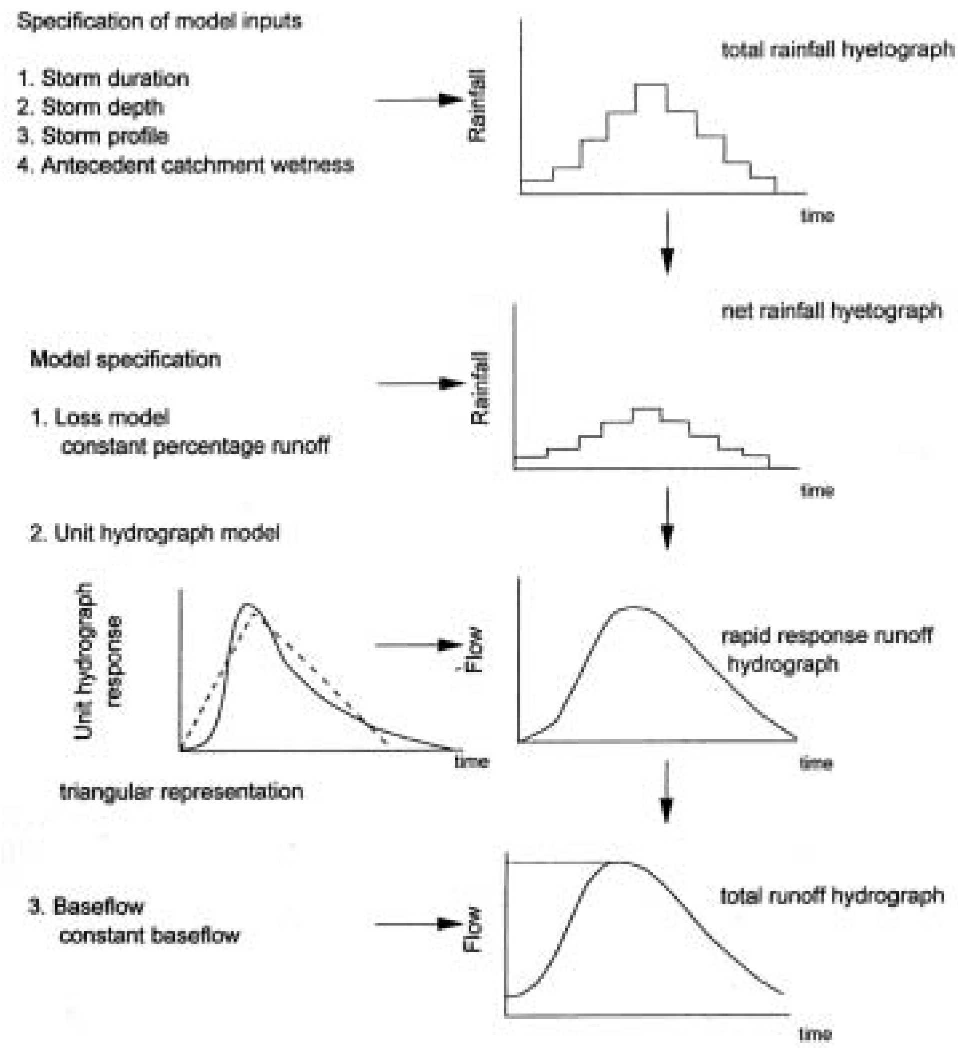


Figure 1.2 Flood estimation using the FSR rainfall-runoff method (Houghton-Carr, 1999)

1.2.5 Flood Estimation Handbook

Following the continued publication of FSSR and IH reports, it became increasingly difficult for users to fully understand the most up-to-date guidance regarding the FSR rainfall-runoff method. According to Reed (1999) the difficulties were exacerbated by the successful penetration of FSR methods into other methods and software products. The method had been adopted or taught in many settings, including hydrology textbooks, engineering guides on reservoir safety (ICE, 1996) and the internal documents of agencies and consultants. Increasingly, stating that a design was based on the FSR procedure no longer assured that the most up-to-date procedure had been used (Reed, 1999).

A major advance in flood risk estimation in the UK was the release of easily accessible digital catchment descriptors for all catchments draining an area of at least 0.5 km^2 (Bayliss, 1999). As part of the FEH research programme, the FSR rainfall-runoff method was updated (Houghton-Carr, 1999), although the model at the core of the design method remained unchanged. The parameter equations were updated, based on the new digital catchment descriptors and, in addition, a new DDF model was developed (Faulkner, 1999) and incorporated into the FEH rainfall-runoff method.

1.2.6 Post FEH

The FEH rainfall-runoff method, combined with the FEH DDF model, 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 located in north-west England and, subsequently, by Ashfaq and Webster (2002) in a study of 88 catchments located throughout the UK. The original FSR design model was calibrated using the FSR DDF model and the combination of the FSR design model with the FEH DDF model is generally believed to result in design flood 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. As a result, Defra and the Environment Agency initiated the current 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.

1.3 The ReFH method

The Revitalised Flood Hydrograph (ReFH) 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;
- 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. It is hoped that the improved physical representation of the hydrological system offered by the ReFH model will facilitate its acceptance by end users.

1.4 Linkage with other EA/Defra Projects

Project FD1913 is part of the Fluvial, Estuarine and Coastal Processes theme of the Joint Defra/Environment Agency Flood and Coastal Management R&D Programme. Two other research studies within this theme are of direct relevance to the revitalised rainfall-runoff method. Project SC040029 *Dissemination of the Revitalised FEH rainfall-runoff method* aims to provide dedicated software packages to allow the implementation of the ReFH design model as described in this report, and will also deliver a supplementary report to FEH Volume 4. The supplementary report will contain a description of the Revitalised FSR/FEH rainfall-runoff method aimed towards the user community rather than detailing the research and development issues as in the present report. The dissemination project will ensure that all FEH users are made aware of the results of the current study and the revised rainfall-runoff method for hydrological design. Project FD1919 *Evaluation of the mapping and assessment of urban and suburban areas* is using updated land cover data to improve the indexing of urban areas within the FEH procedures and its recommendations will be accompanied by an upgraded version of the FEH CD-ROM during 2005.

Two further projects within the Broad Scale Modelling theme of the Joint Programme are using a continuous simulation approach to develop a new method of flood frequency estimation that can be applied across the UK. Project FD2106 *National river catchment flood frequency method using continuous simulation* is using catchment modelling of the complete flow time series (rather than an event-based approach) to provide flood statistics at both gauged and ungauged sites. In the practical application of the method, continuous rainfall data and/or simulated rainfall series are required and project FD2105 (*Improved methods for national spatial-temporal rainfall and evaporation modelling*) is researching a range of rainfall modelling tools.

1.5 Structure of the report

This report presents the results of the analyses undertaken during the current project. Chapter 2 contains details of the data available to the project. The Flood Event Archive (FEA) held at CEH Wallingford was found to be dominated by data for events of relatively low magnitude. During the project, the FEA was updated to include data for more recent flood events and also to increase the number of ‘large’ events available to the analysis. Details of the 101 catchments in Great Britain included in the final analysis are tabulated in Appendix E.

Chapter 3 describes the structure of the ReFH model which has been developed to replace the FSR/FEH unit hydrograph and losses model. The material in this chapter is intended as an overview, and more detailed descriptions of the individual model components can be found in the accompanying Appendices A, B, C and D. In Chapter 4, the next stage of the analysis is described, which refined the ReFH model, reducing the number of parameters and making model application more practical. The final form of ReFH was applied to 101 catchments using a two-stage optimisation procedure.

Chapter 5 describes the development of new design rainfall inputs to the ReFH model. Although the study has retained the use of the FEH DDF model, an analysis of seasonal rainfall frequency for durations of 1 hour and 1 day has been used to develop seasonal correction factors which are applied to the all-year design depth values. In Chapter 6, details are given of the development of the ReFH design model including the derivation of design values of antecedent soil moisture content. Details of a regression analysis undertaken to develop equations to relate the ReFH model parameters to the catchment descriptors available on the FEH CD-ROM are given in Chapter 7. The resulting predictor equations will allow hydrologists to estimate the ReFH model parameters at ungauged sites. Chapter 8 contains a validation of the design model when applied to both gauged and ungauged sites. The validation confirms that the design model for most catchments can be expected to yield estimates of design peak flow broadly in agreement with the corresponding estimates obtained from pooled statistical analysis of annual maximum (AMAX) series. The final conclusions of the research are presented in Chapter 9, together with details of planned dissemination activities and recommendations for future research.

2. Updating of the Flood Event Archive (FEA)

2.1 Introduction

The basis of the FSR rainfall-runoff method, which was published in 1975, was the analysis of a large number of flood events on over 140 catchments in Great Britain. The four main criteria for selection of the catchments were as follows (FSR I.6.3):

- catchment area should not exceed 500 km^2;
- reliable gauging station ratings should be available;
- one or more autographic raingauges on or near the catchment were required;
- catchments should display some evidence of a short-term response to heavy rainfall.

The number of events chosen per catchment ranged from two to 25, with an average of 10. No suitable catchments were found in Northern Scotland and Northern Ireland.

Following the publication of the FSR, new flood event data were assembled as further research was undertaken, culminating in the publication of Supplementary Report FSSR16 (IH, 1985). At that time a computer database management system, the Flood Event Archive (FEA), was set up to hold the data, and relatively few new events had been added to the archive by the time the current project commenced.

At the outset of this project, the FEA comprised approximately 4000 events for 286 catchments and thus represented a major resource. However, the dataset was found to be dominated by relatively small flood events. A principal objective of the current project was to increase the proportion of events of high magnitude available to the analysis. Therefore, during the first phase of the project, a scoping study was undertaken to review existing archives of flood event data throughout England and Wales (later extended to include Scotland) and to identify additional sources of data to allow the analysis to focus on events of greater magnitude. An additional objective of the study was to determine appropriate criteria for identifying ‘large’ events.

2.2 Scoping study

Details of the scoping study are given in Interim Report 1 (Stewart *et al.*, 2002) and only a summary of the main results is given here.

Firstly, a review of the data held in the FEA was undertaken with the co-operation of gauging authorities and others with relevant expertise. The locations of the 286 catchments are shown in Figure 2.1. The aim of this exercise was to ascertain whether the event data could still be considered reliable, for example where new information for a gauged site was available, or where the use of a new rating curve had resulted in retrospective changes to the flow record. Reviewers were asked to comment on the quality of individual gauging stations, bearing in mind that the flows being considered were generally in the high flow range. Reviewers were also asked to compare the peak flows for a sample of the events with those held in their own archives to identify any major differences. This process led to the rejection of 15 catchments from the original total of 286.

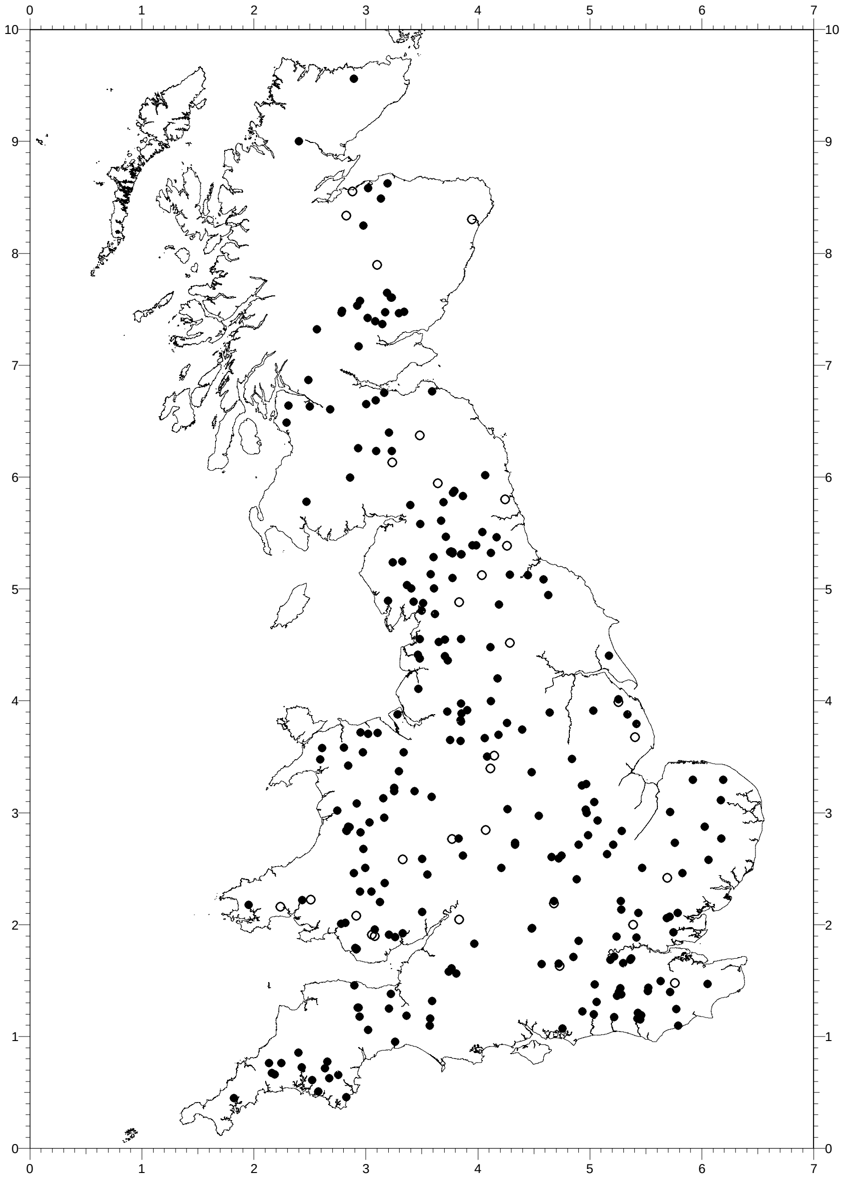


Figure 2.1 Locations of catchments currently included in the project database

- ● Flood Event Archive data
- ○ New data selected from continuous simulation modelling dataset

An initial survey suggested that only 23% of the total number of events in the existing FEA had a peak flow that exceeded the at-site estimate of QMED, the median annual flood, which corresponds to a return period of only 2 years.

The range of catchment types included in the FEA dataset was investigated by reference to some of the key digital catchment descriptors used in FEH methods. Frequency distributions of nine catchment descriptors (*AREA, BFIHOST, DPLBAR, DPSBAR, FARL, PROPWET, SAAR, SPRHOST* and *URBEXT*) were examined to determine whether any particular types of catchment were obviously under-represented in the data. The results showed that there was generally a good range of catchment types. The catchments cover a fairly good range of *SAAR* values and slopes, and the distributions of *FARL* and *URBEXT* were found to be largely indicative of the type of catchments analysed in the FEH. The main deficiency in the FEA dataset was in catchments with low *SPRHOST* values (i.e. permeable catchments). The detailed analysis of permeable catchments was considered to be outside the scope of the current project, but details of a similar modelling study can be found in Packman (2004).

2.3 Updating and augmentation of the FEA

The research plan for the project stated that the research should include data for larger storms from 30 to 50 catchments in England and Wales. Thus the analysis has focused on those events in the FEA whose peak flow exceeds the value of QMED, and those that exceed half the QMED value for catchments new to the archive. An extended FEA was set up to largely replicate the existing archive and to allow the original FEA to remain ‘frozen’ in time.

The second objective of the scoping study was to identify possible sources of additional flood event data to allow the existing FEA to be updated and extended to include a greater number of events of relatively high magnitude, such as the floods of Easter 1998 and Autumn 2000. External reviewers were therefore requested to suggest dates for large flood events at any of the FEA sites, as well as to suggest new catchments where gauged flows were known to be reliable. Some data for individual events were added to the extended FEA as a result.

The data set being compiled by the team at CEH working on project FD2106 to develop a new flood frequency estimation method using a continuous simulation approach (see Section 1.4) provided a readily available source of additional flood event data for catchments in Great Britain. The hourly time series of rainfall and flow data were scanned and appropriate events selected according to the criteria outlined above. Data collected in the period 1996 to 2001 were found to be relatively ‘flood rich’ and the proportion of large events (exceeding the value of QMED) for these new catchments increased to 32% of the total selected.

3. The Revitalised Flood Hydrograph model

This chapter describes the structure of the Revitalised Flood Hydrograph (ReFH) rainfall-runoff model. Each individual model component is introduced and reference is made to more detailed descriptions which can be found in the Appendices. The Revitalised FSR/FEH rainfall-runoff method is based on the ReFH model.

3.1 Motivation

As discussed in Chapter 1, following the publication of the FEH in 1999 and its restatement of the FSR rainfall-runoff method, users of the method highlighted a number of concerns about the structure of the underlying model, and drew attention to possible inconsistencies deriving from the introduction of the new FEH design inputs. The main concern was centred on the tendency of the method to overestimate flood peaks when compared to flood frequency curves derived from the FEH statistical method. Other issues include:

- the adoption of updated, and typically larger, design storm rainfall estimates;
- the adoption of different design rainfall and flood return periods for rural catchments but not for urban ones;
- the influence of seasonal variation of rainfall and soil moisture not accounted for in the model;
- the effect of urbanisation on the timing and magnitude of flood events;
- possible variation of percentage runoff with event magnitude.

Moreover, the relatively small size of the flood events available to the Flood Studies team when the model was calibrated may be a limitation of the original analysis. To address this problem, during the early stages of the project, the FEA was updated with relatively large flood events recorded in recent years as described in Chapter 2.

A particular concern raised by Packman (2004) is the use of the catchment wetness index (CWI) to represent antecedent soil moisture condition. The CWI component is formed by combining an index of rainfall in the five previous days (API5) with the Met Office's estimate of soil moisture deficit (SMD) at the onset of the event using the ESMD calculations. By combining API5 with SMD, the CWI index is double-counting the previous five days' rainfall. Furthermore, the Met Office no longer performs the ESMD calculations and, indeed, the present MORECS calculations of SMD are also about to be replaced by a new system, Nimrod/MOSES. In the light of these difficulties, a more consistent approach is to estimate antecedent soil moisture independently of the SMD procedures provided by the Met Office.

When estimating the T-year flood using the FSR/FEH rainfall-runoff method, the value of CWI is determined from catchment average annual rainfall (*SAAR*). This is another limitation of the method as it could lead to similar values of CWI being applied to adjacent rural and urban catchments, which is clearly inappropriate.

According to Packman (2004), some of the perceived problems with the FSR/FEH rainfall-runoff method may relate to the analytical procedures used for modelling baseflow and percentage runoff. The FEH equations for estimating baseflow

$$BF = \left(33\left(CWI - 125\ \right) + 3.0\ SAAR + 5.5\ )\ 10^{-5}\ AREA\right) \tag{3.1}$$

and percentage runoff, *PR*, (for rural catchments),

$$PR = SPRHOST + 0.25\left(CWI - 125\right) + 0.45\left(P - 40\right)^{0.7} \tag{3.2}$$

where *P* is the depth of the storm event in mm, are derived models, fitted to the results of analysing individual events. The equations are not linked directly to the procedures used in analysing those events and do not attempt to model the governing hydrological processes explicitly.

The ReFH model has been developed explicitly to address the concerns raised above and thereby to provide a more physically-based approach to flood event modelling.

3.2 The ReFH model

The ReFH model consists of the same three main components as the original FSR/FEH model: a loss model, a routing model and a baseflow model. All three components have undergone review and, consequently, have been replaced by new improved techniques. The connections between the three model components are shown in Figure 3.1 together with the required input variables and model parameters.

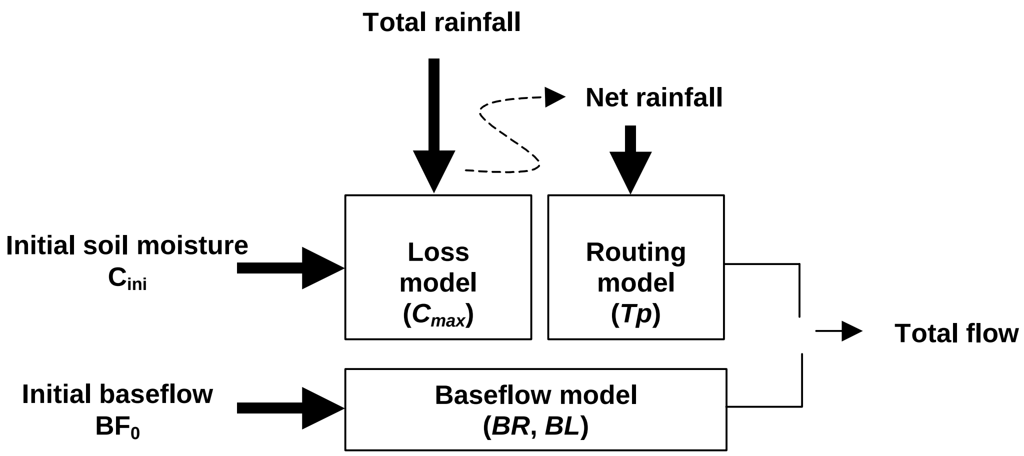


Figure 3.1 Schematic representation of the ReFH model

When simulating a flood event, the loss model is used to estimate the fraction of total runoff 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 in the following sections.

3.2.1 The 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 currently being used in a study to develop a national system for flood frequency estimation using continuous simulation modelling in the UK (Calver *et al.*, 2004). Furthermore, the model has been used in real-time flood forecasting (Moore, 1999) and recently 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 be divided into a number of individual storage elements, where C is soil moisture capacity. The depth of water in each storage element is increased by rainfall, P, depleted by evaporation, and when rainfall exceeds the storage capacity it generates direct runoff, q.

If the soil moisture capacities for each of the storage elements are arranged in order from the highest (C_{max}) down to zero capacity, the uniform PDM assumes a distribution of soil moisture capacity as shown in Figure 3.2, where the horizontal axis represents the cumulative distribution. Thus, the probability of a storage element being smaller or equal to the maximum capacity equals 1, or in mathematical terms P{$C \leq C_{max}$} = 1.

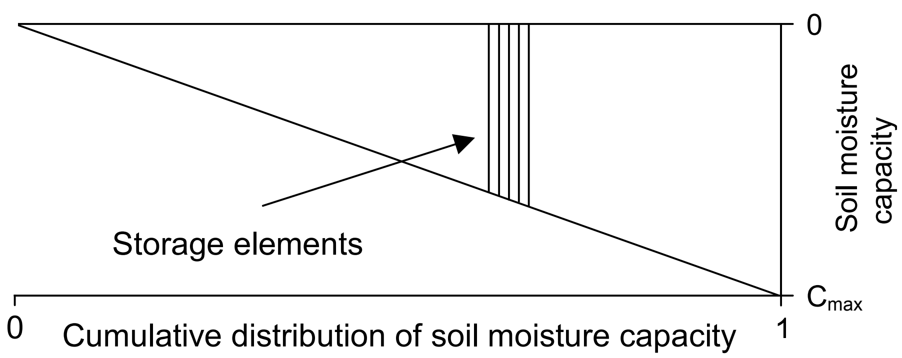


Figure 3.2 Basin representation of storage elements of different depth

It is further assumed that the storage elements interact such that between rainfall events, the soil moisture is redistributed between stores. Thus, soil moisture C is constant for all elements of capacity greater than C and is at full capacity for elements of capacity smaller than C_t, as illustrated in Figure 3.3.

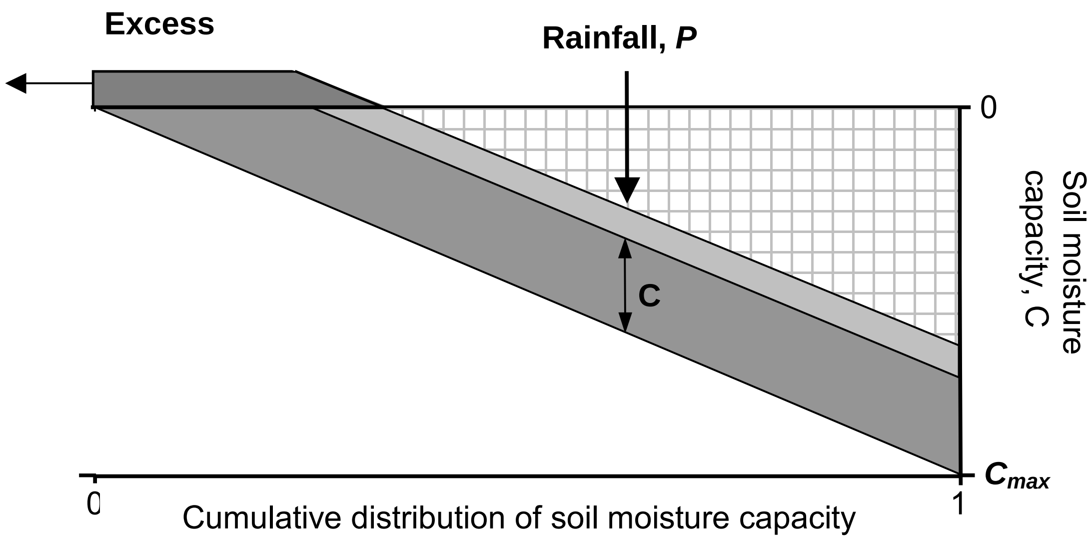


Figure 3.3 Equal water content, *C*, across stores of different capacity

A pulse of rain (P_t) on the soil thus gives 100% runoff from the area already at full capacity and increases the moisture content in all other areas. When at time t, a rainfall volume P_t is imposed on a catchment with soil moisture storage C_t, the excess amount of rainfall converted into direct runoff, q_t, can be estimated through simple geometric considerations as

$$\frac{q_t}{P_t} = \frac{C_t}{C_{\max}} + \frac{P_t}{2C_{\max}} \qquad \text{for } t = 1, 2, 3, \ldots \tag{3.3}$$

$$C_{t+1} = C_t + P_t$$

where q/P is the ratio of rainfall transformed into direct runoff, i.e percentage runoff, and C_{max} is the only model parameter. If the soil storage is filled during an event, the relationship in Eq. (3.3) changes to

$$\frac{q_t}{P_t} = 1 - C_{\max}\frac{\left(1 - C_t / C_{\max}\right)^2}{2P_t} \tag{3.4}$$

As the model assumes no flux of water out of the soil during an event, Equation 3.4 is only relevant for that particular timestep where the soil content would have exceeded maximum capacity. In all the following time steps the soil is at full capacity, i.e. q/P = 1.0, corresponding to 100% runoff. Further background information on the loss model and the derivation of these relationships is given in Appendix A.

The loss model in ReFH differs from the concept used in the FSR/FEH loss model. The losses in the ReFH model are derived as the event unfolds, rather than being a value fixed before the onset of the event, as is the case in the FSR/FEH model. Note, however, that the model form used in the original FSR work did allow losses to change during an event when analysing observed events, but the additional computation was considered to yield insignificant benefits when modelling design storms, hence the constant percentage loss in the FSR design model.

3.2.2 The routing method

The ReFH model uses the unit hydrograph (UH) concept for routing the net rainfall to the catchment outlet (direct runoff). The original FSR/FEH model adopted a standard triangular-shaped unit hydrograph scaled to each catchment using the time to peak (*Tp*) parameter. The peak of the UH was fixed at Q_p = (220 / *Tp*)*(AREA /100), where the constant 220 assumes AREA in km^2, *Tp* in hours and *Qp* in m^{3}s^{-1}/10 mm of effective rainfall.

The ReFH model contains the concept of a standard instantaneous unit hydrograph (IUH) shape scaled to individual catchments, but introduces a more flexible shape as shown in Figure 3.4 below.

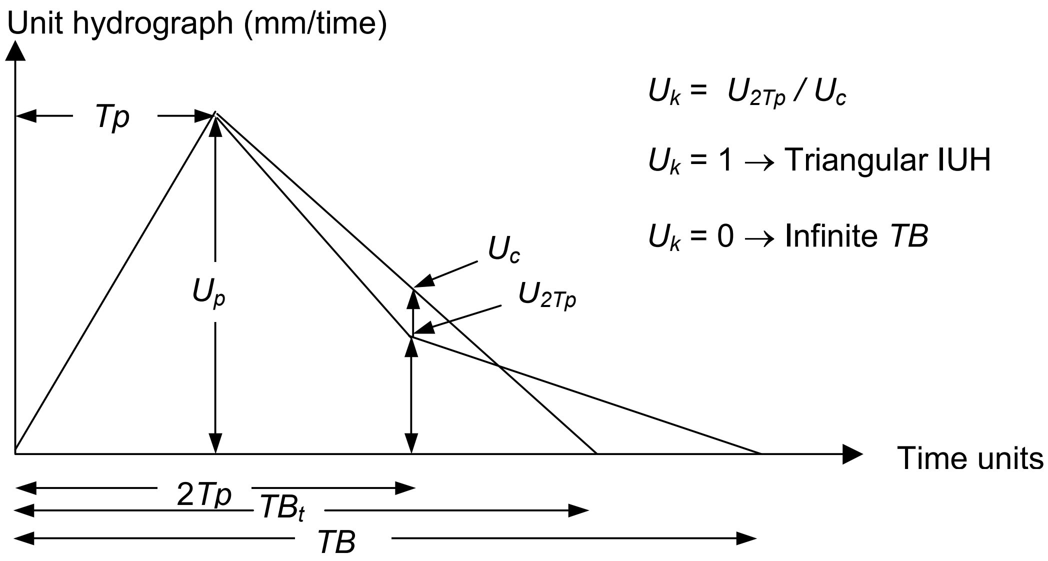


Figure 3.4 Standard IUH adopted in ReFH

The new standard IUH shape is a kinked triangle described by a time scaling parameter, *Tp*, and two dimensionless numbers, U_p and U_k. Since the volume under the dimensionless IUH must equal unity, for a simple triangular IUH, the volume $U_p(TB_t/Tp)/2$ must equal 1, or rearranging:

$$U_p=2\,(Tp/TB_t) \qquad (3.5)$$

So noting the FSR triangular relationship of $TB_t = 2.525\ Tp$, it can be seen that the FSR $QpTp=220$ expression is equivalent to an U_p value of 0.792. It may also be noted that an U_p value of 1 forms an isosceles triangle, for which $QpTp$ would equal 273.

The parameter U_k is a multiplier applied to the ordinate U_c of the triangular IUH at $2Tp$:

$$U_c=U_p(TB_t-2Tp)/(TB_t-Tp) \tag{3.6}$$

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.

$$TB = (1+2(1-U_p)/(U_k\ U_c\ ))Tp \tag{3.7}$$

The IUH is converted to a UH for the required time step, ΔT, by using the S-curve method.

Having determined the shape of the IUH, the routing of the net rainfall to the catchment outlet is carried out using the well-known convolution equation:

$$q_t = \sum_{i=1}^{t} P_i u_{t-i+1} \qquad \text{for } t = 1, 2, 3, \ldots \tag{3.8}$$

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.

The S-curve method

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 timesteps ΔT, the IUH must first be converted to an equivalent 'TUH'. To transform the IUH in Figure 3.4 into a unit hydrograph of any given timestep, the ReFH model uses the S-curve method as described in many standard hydrology textbooks such as Chow *et al.* (1988) and Wilson (1990). The S-curve method replaces the existing FEH approximation of adding half the considered time step to the unit hydrograph time to peak $Tp(0)$. This approximation works only if ΔT is a small component of Tp and the unit hydrograph is not too skewed.

An S-curve, s_t, is a summation of the unit hydrograph, u_t, and describes the flow resulting from imposing a continuous uniform-intensity storm on the considered catchment. Having obtained the S-curve for the IUH, the unit hydrograph for a given duration ΔT is obtained by offsetting the S-curve by a distance ΔT thereby creating a new S-curve, s_t', where

$$s_t' = s_{t-\Delta T} \tag{3.9}$$

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.

$$u_t' = \frac{1}{\Delta T}\left[s_t - s_{t-\Delta T}\right] \tag{3.10}$$

In practice, this equation is equivalent to defining the unit hydrograph at time n*t* as the volume under the IUH between time step (n-1)*t* and n*t*.

3.2.3 The baseflow model

The constant baseflow rate adopted in the FSR/FEH model has been replaced in ReFH by a model based on the linear reservoir concept, where storage in the baseflow reservoir is assumed to be linearly related to baseflow rate by a time parameter equivalent to the mean lag time between inflow (recharge) and outflow (baseflow) and is thus denoted as baseflow lag (*BL*). Under baseflow recession conditions (beyond the end of quick response runoff), the factor between successive ordinates of recession a time *t* apart is given by exp(-*t*/*BL*). Recharge in the ReFH model is directly related to the rainfall excess given by the loss model, on the assumption that only the same wet area that generates runoff has excess soil moisture to generate recharge. The recharge fraction is denoted by *BR*. The baseflow model can be developed as a recurrence formula and links baseflow to surface runoff as

$$BF_t = \frac{1}{1-K_2}\left[K_1 q_{t-1} + K_2 q_t + \left(K_1 + K_3\right)BF_{t-1}\right] \qquad \text{for } t = 1, 2, 3, \ldots \tag{3.11}$$

where q_t is the direct runoff defined by the routing model and the coefficients K_1, K_2 and K_3 are constants and functions of the two baseflow parameters *BR* and *BL*. The analytical expressions can be found in Appendix B and are similar to those used in the Muskingum method of river routing. The actual model parameters are the baseflow recharge, *BR*, the baseflow Lag, *BL*, and the initial baseflow, BF_0. For a more in-depth description of the model and the rationale behind the choice of model, please refer to Appendix B.

3.2.4 Antecedent soil moisture

In the FSR/FEH model, the soil moisture content at the onset of a flood event was characterised by the catchment wetness index (CWI). As discussed in Section 3.1, the use of CWI is considered obsolete for both theoretical and practical reasons.

In the ReFH model, the antecedent soil moisture content (C_{ini}) is modelled using a separate daily soil moisture accounting model driven by continuous daily records of rainfall and evaporation as

$$m_{t+\Delta t} = m_t + \left(p_t - q_t\right) - d_t - e_t \tag{3.12}$$

where m_t is soil moisture, *p* is rainfall, *q* is runoff, *d* is drainage and *e* 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 estimate.

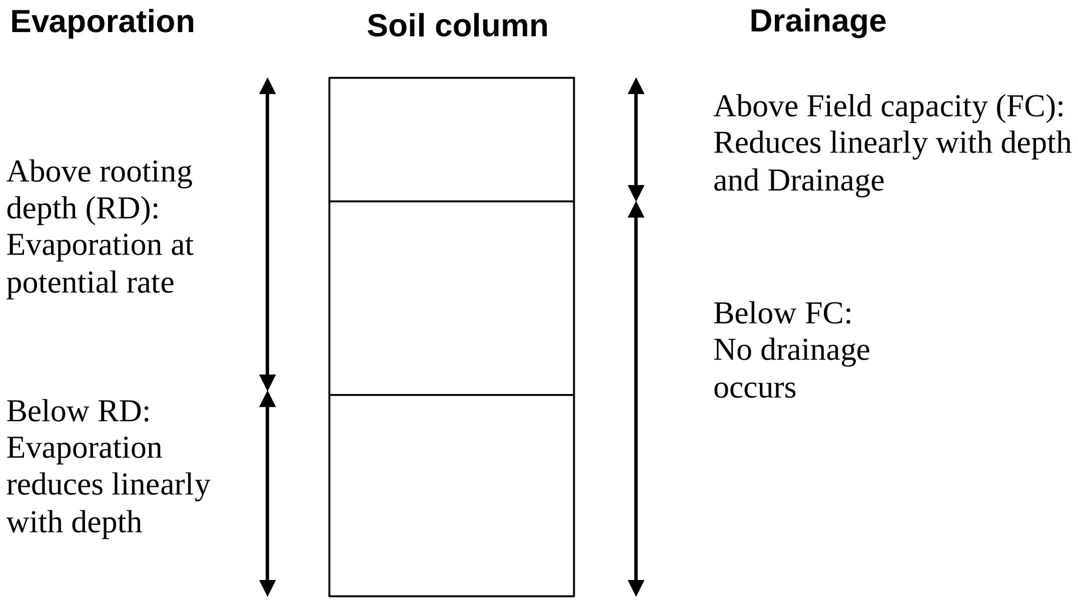


Figure 3.5 Soil moisture model

When soil moisture content exceeds *FC*, water is lost by drainage defined as

$$Drainage = DK\,(\,m - FC\,) \qquad (3.13)$$

where *m* is actual soil moisture content. Combining this equation with the continuity equation describing drainage (*dm/dt=-drainage*) and integrating over a daily time step gives an expression relating the parameter *DK* to the daily decay rate. In this project, a constant value of *DK* = 0.8 for the daily decay rate has been applied.

The actual evaporation equals the potential evaporation as long as the soil moisture content is above *RD*. When the soil moisture content falls below *FC*, drainage no longer occurs but the actual evaporation still equals the potential rate. Once the soil moisture falls below RD, the actual evaporation reduces linearly with depth as

$$E_a = \frac{m}{RD} E_p \qquad (3.14)$$

where *RD* is the rooting depth as defined in Figure 3.5 and *m* is the actual soil moisture content. Daily potential evaporation is estimated from a climatological average sequence fitted to monthly average potential evaporation values (1960-90) derived from published MORECS data. A second order Fourier series is fitted to the catchment average potential evaporation values found by area weighted average of the MORECS squares falling within the catchment.

When rainfall occurs, the runoff is estimated by the linear PDM relationship and only the residual rainfall is added to the soil moisture. To get the antecedent soil moisture content at the onset of the event, the soil moisture accounting model is used to model the continuous soil moisture for a running period assuming soil moisture at field capacity on 1 January the year before the actual year in which the event occurred (see Figure 3.6). The soil moisture accounting model is run at a daily time step up to the day of the event and then with a single time step which is set to a fraction of a day corresponding to the time from 09:00 am to the time of occurrence of the event.

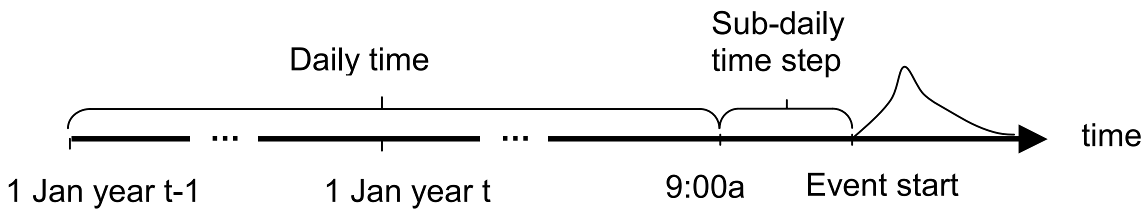


Figure 3.6 Time scale for modelling of antecedent soil moisture

This soil moisture accounting model is part of a daily rainfall-runoff model (DAYMOD) described in Appendix D. In addition to the soil moisture accounting model described above, the DAYMOD model uses the same baseflow model as the ReFH model and either a simple linear reservoir or a triangular unit hydrograph quick response runoff model. The DAYMOD model can be calibrated when sufficiently long continuous records of daily rainfall, evaporation and flow are available. In a study of the flood hydrology of the upper River Thames, (Packman, 2003) showed that application of DAYMOD with daily values of rainfall and runoff gave results comparable with the corresponding results obtained using sub-daily data. Hence, given the similarities between the two models, it is considered reasonable that certain parameters in DAYMOD are transferable to the ReFH model.

The linkage between the soil parameters in DAYMOD and the maximum soil moisture capacity (C_{max}) in the ReFH model is given as

$$C_{\max} = 2 \times FC \times SM \tag{3.15}$$

where *FC* is obtained from the DAYMOD model and *SM* is obtained from direct analysis of the hourly flow and rainfall data using the ReFH model, respectively.

3.3 Overall model fitting

The ReFH structure and model components described above are relatively modest updates to the original FSR/FEH model structure, but a more significant improvement in model fitting has been introduced. Automatic assessment and optimisation of all model parameters has been carried out as a complete system, rather than by *a priori* separation of baseflow and rainfall losses.

4. Analysis of Flood Events

4.1 Introduction

The original formulation of the ReFH model, as described in the previous chapter, had a total of nine parameters and three boundary conditions. This chapter describes a sensitivity analysis of the ReFH model which was undertaken to refine the parameters structure and to investigate the most appropriate optimisation strategy considering the available data material. The final model structure, described by four parameters and two boundary conditions, was used to analyse observed flood events from 101 catchments in England, Wales and Scotland. For each of these catchments, the parameters of the ReFH model were estimated using an autocalibration procedure.

4.2 Autocalibration procedure

During the early stages of the analysis, the parameters of the ReFH model were estimated for a number of test catchments using a multivariate optimisation scheme based on the hill-climbing method of Rosenbrock (1960). This initial application of ReFH, reported in Packman *et al.* (2003), used the recession curve from each flood event to estimate the baseflow parameters, *BL* and *BF*, and then went on to estimate C_{ini}, C_{max}, and the unit hydrograph jointly through an updated version of the matrix-inversion method of deconvolution described in FSR I.6.4. Subsequent research developed the soil moisture model so that initial soil moisture condition (C_{ini}) for each event could be estimated directly rather than being included in the optimisation scheme. The soil moisture accounting model, which uses daily rainfall and evaporation data, was set up to simulate the soil moisture condition continuously from 1st January in the year preceding that in which the event occurred until the start of the event itself.

With respect to the routing model, it was decided to optimise the parameters of the kinked triangular unit hydrograph directly rather than to use matrix-inversion (deconvolution) and subsequently fit a kinked-triangle. This simplification considerably reduced the time required to undertake the analytical procedures. The final optimisation scheme is illustrated in Figure 4.1, where the dashed lines indicate the optimisation functionality.

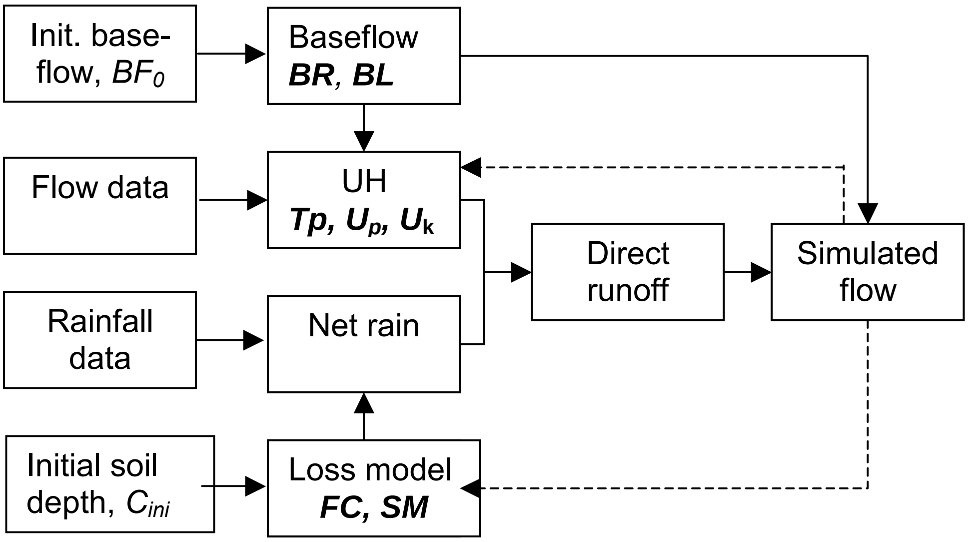


Figure 4.1 Autocalibration scheme for ReFH

The optimisation scheme allowed for the model parameters to be estimated through the use of single or multiple events, and used an objective function defined as the squared difference between observed and simulated runoff, i.e. the mean square error (*MSE*):

$$MSE = \frac{1}{M}\sum_{m=1}^{M}\sum_{t=1}^{N_m}\left(Qsim_{t,m} - Qobs_{t,m}\right)^2 \qquad (4.1)$$

where M is the total number of events available for the catchment under consideration and N_m is the duration of the mth event. Only catchments with a minimum of five ($M \geq 5$) events of which at least one is larger than QMED (the median annual maximum flood) were included in the analysis. This data screening was done at an earlier stage of the project , and the estimate of QMED for each catchment was obtained from the data set provided with the FEH statistical procedure in Robson and Reed (1999).

4.3 Baseflow parameters

Before the optimisation module was applied, estimates of the two baseflow parameters, *BL* and *BR*, were obtained. The method for estimating *BL* and *BR* was based on the analysis of hydrograph recessions performed on individual events. The final estimate for a specific catchment was then derived 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' as illustrated in Figure 4.2.

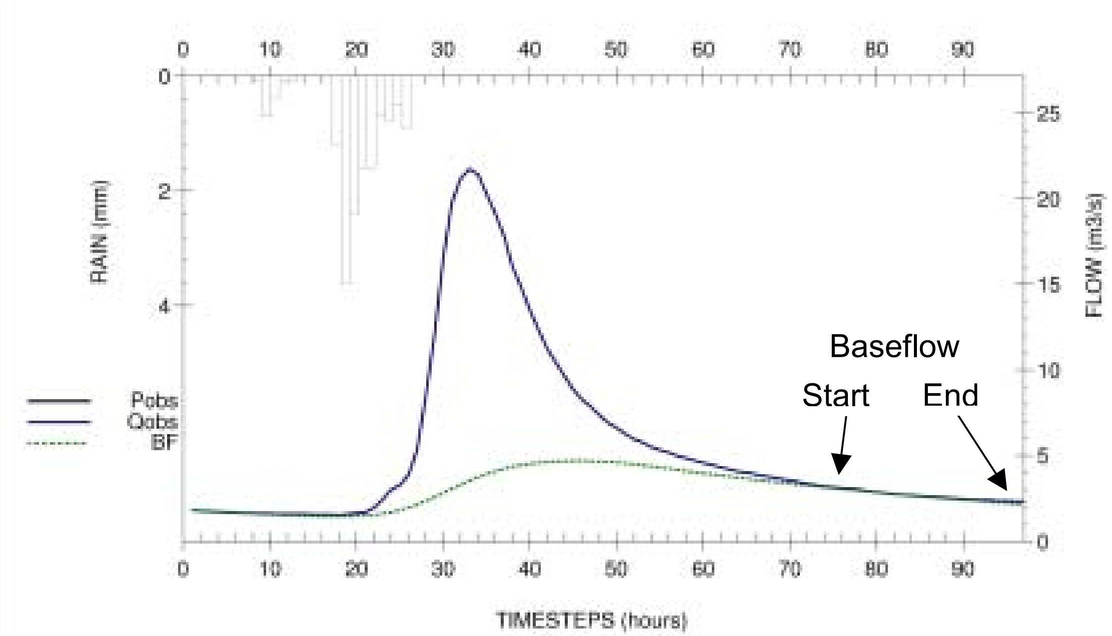


Figure 4.2 Selection of points for baseflow estimation

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). For a number of events, especially from the original FEA, the two baseflow parameters could not be estimated as they did not have a sufficiently long recession. Figure 4.3 shows an example of such an event.

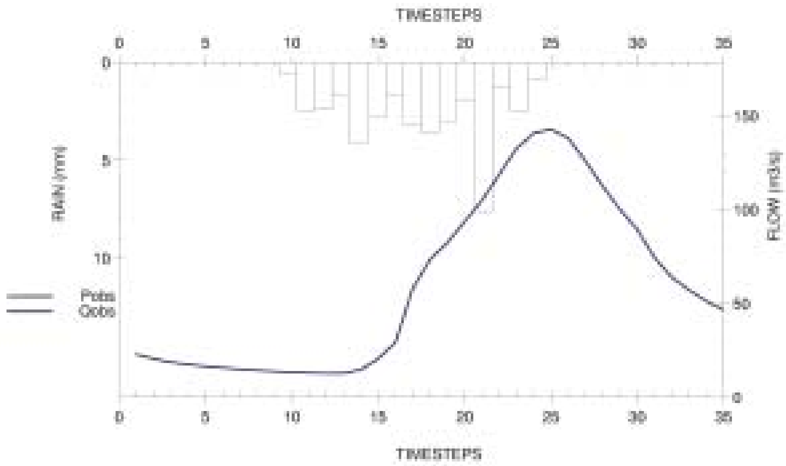


Figure 4.3 Example of event not included in the analysis

A number of different strategies for estimating the catchment average baseflow parameters were tested, including direct optimisation and using values obtained from DAYMOD (as with soil parameters – see Section 3.2.4).

However, apparent differences in parameters arose, which needed more detailed investigations. Thus, for this study, the baseflow parameters were estimated individually for all the events on each catchment with sufficiently long recessions and averaged to provide catchment values.

4.4 Sensitivity analysis

4.4.1 Introduction

The purpose of the sensitivity analysis was to investigate and determine the most appropriate parameter structure taking both practical and modelling issues into consideration. The sensitivity analysis was conducted on a limited sample of test catchments but in practice there was additional feedback and experience gained by initial calibration of the ReFH model to the entire data set with most parameters included in the autocalibration scheme. The initial ReFH model structure has nine parameters and three boundary conditions. For some catchments the total number of observed flood events is less than nine. As a result, the ReFH model appears over-parameterised for practical use and, therefore, it is necessary to reduce the number of free parameters by fixing the least sensitive at sensible values.

When developing a generic modelling system for use at any site in the UK from the information available in a finite sample of observed flood events, there are a number of issues that should be considered. The ReFH model is developed under a certain set of assumptions and the model is therefore expected to perform well on a catchment which conforms to these assumptions. In practice, users are likely to come across catchments that deviate from the theoretical assumptions and it is important that in these cases the user applies sound hydrological judgement and understands the background and limitations of a generic method.

In the context of the sensitivity analysis it should be noted that fixing model parameters will reduce the number of free parameters to be estimated, thereby enhancing practical ease of use. The downside, however, is that by fixing a parameter some of the more advanced model's flexibility will be lost and the resulting lack of fit will have to be absorbed by the remaining model parameters. By fixing too many parameters, cases might be encountered where no reasonable modelling results can be obtained or that relatively few available free parameters have to be adjusted to unrealistic values. The final choice of model structure has to be a pragmatic view considering the loss of flexibility with the increase in user friendliness and ability to develop a method for spatially generalising the ReFH model to any catchment in the UK.

The sensitivity analysis was carried out for 14 catchments selected to cover a wide range of catchment types encountered in the UK. The catchments, together with key catchment descriptors obtained from the FEH CD-ROM (Bayliss, 1999), are listed in Table 4.1.

Table 4.1 Catchments included in sensitivity analysis

Catchment	Name	*Easting*	*Northing*	*AREA* (km^2)	*SAAR* (mm)	*BFIHOST*	*SPRHOST* (%)	*FARL*	*DPLBAR* (km)	*DPSBAR* (m/km)	*URBEXT* 1990
19002	Almond at Almond Weir	300250	665150	44.36	1016	0.364	47.0	0.998	10.74	37.76	0.0327
24004	Bedburn Beck at Bedburn	411950	532150	74.32	894	0.362	43.8	0.999	9.62	109.67	0.0007
25005	Leven at Leven Bridge	444500	512100	193.57	726	0.381	40.5	0.998	25.49	75.96	0.0099
28039	Rea at Calthorpe Park	407150	284750	74.06	781	0.512	34.9	0.956	8.12	45.32	0.3305
30004	Partney Lymn at Partney Mill	540350	367500	59.94	685	0.570	32.4	0.980	9.40	54.22	0.0110
34007	Dove at Oakley Park	617400	277050	140.10	585	0.427	37.3	0.997	14.16	15.43	0.0101
35008	Gipping at Stowmarket	605950	257850	127.43	577	0.401	43.4	0.998	8.80	25.05	0.0201
39022	Loddon at Sheepbridge	471850	165050	176.49	735	0.594	26.4	0.931	19.24	33.54	0.0454
41028	Chess Stream at Chess Bridge	521850	117400	24.96	850	0.499	35.9	0.984	6.42	48.40	0.0118
46005	East Dart at Bellever	265750	77650	22.29	2096	0.362	47.5	1.000	6.22	96.98	0.0000
54034	Dowles Brook at Dowles	376650	276500	42.07	715	0.632	19.2	0.999	7.49	93.30	0.0045
61003	Gwaun at Cilrhedyn Bridge	200400	235000	31.29	1550	0.495	39.1	1.000	5.21	122.07	0.0000
69027	Tame at Portwood	390450	391900	146.60	1212	0.365	42.6	0.926	26.46	124.05	0.1062
74001	Duddon at Duddon Hall	319550	489550	85.69	2265	0.337	53.7	0.986	10.78	215.66	0.0002

To assess the importance of the ReFH model parameters the sensitivity analysis was conducted by, in turn, fixing different sets of model parameters and noting the percentage difference in *MSE*, as defined in Equation (4.1), when compared to the case where no parameter values were fixed, i.e. maximum flexibility.

It was decided to fix the two parameters describing the rooting depth (*RD*) and daily decay rate (*DK*) in the antecedent soil moisture accounting model. The parameter RD specifies the moisture content below which evapotranspiration begins to fall below the full potential rate. The parameter DK defines the factor by which free soil moisture (above field capacity) drains from the soil over a daily time step (i.e. 80% decrease in a day). Based on hydrological judgement of senior staff at CEH in Wallingford, it was decided to fix the two parameters at *RD* = 0.3 and *DK* = 0.8, respectively. Subsequently, the value of *DK* = 0.8 was later revisited and found to be an appropriate choice. The two baseflow parameters *BL* and *BR* were not considered as part of the sensitivity analysis as they are estimated independently of the autocalibration procedure. The Time to peak (*Tp*) and soil moisture scaling factor (*SM*) were chosen as free parameters for each catchment to resemble the existing FSR/FEH method.

By gradually increasing the number of fixed parameters it is possible to assess the importance of the individual model parameters. In Figure 4.4 the labels on the horizontal x-axis indicate which model parameters have been fixed and the y-axis shows the percentage deviation of MSE from the case where the ReFH model has been calibrated with no model parameters being fixed. Starting from left with no fixed parameters (maximum flexibility) moving right until the last bar, where only two free parameters are available (*Tp* and *SM*).

The bars in Figure 4.4 clearly illustrate the loss of flexibility (increasing bar height) as more and more model parameters are fixed. In general, the results for most catchments show that the MSE is less sensitive to the routing model parameters U_p and U_k than of the loss model parameters *DK* and *FC*, i.e. the decrease in flexibility is generally larger when fixing the loss model parameters than the routing model parameters. Note that catchment 25005 behaves differently from the general pattern observed in the remainder of the catchments. No reason for this outlier was identified but possible causes could include problems with local minima in the optimisation procedure or a non-representative sample of flood events.

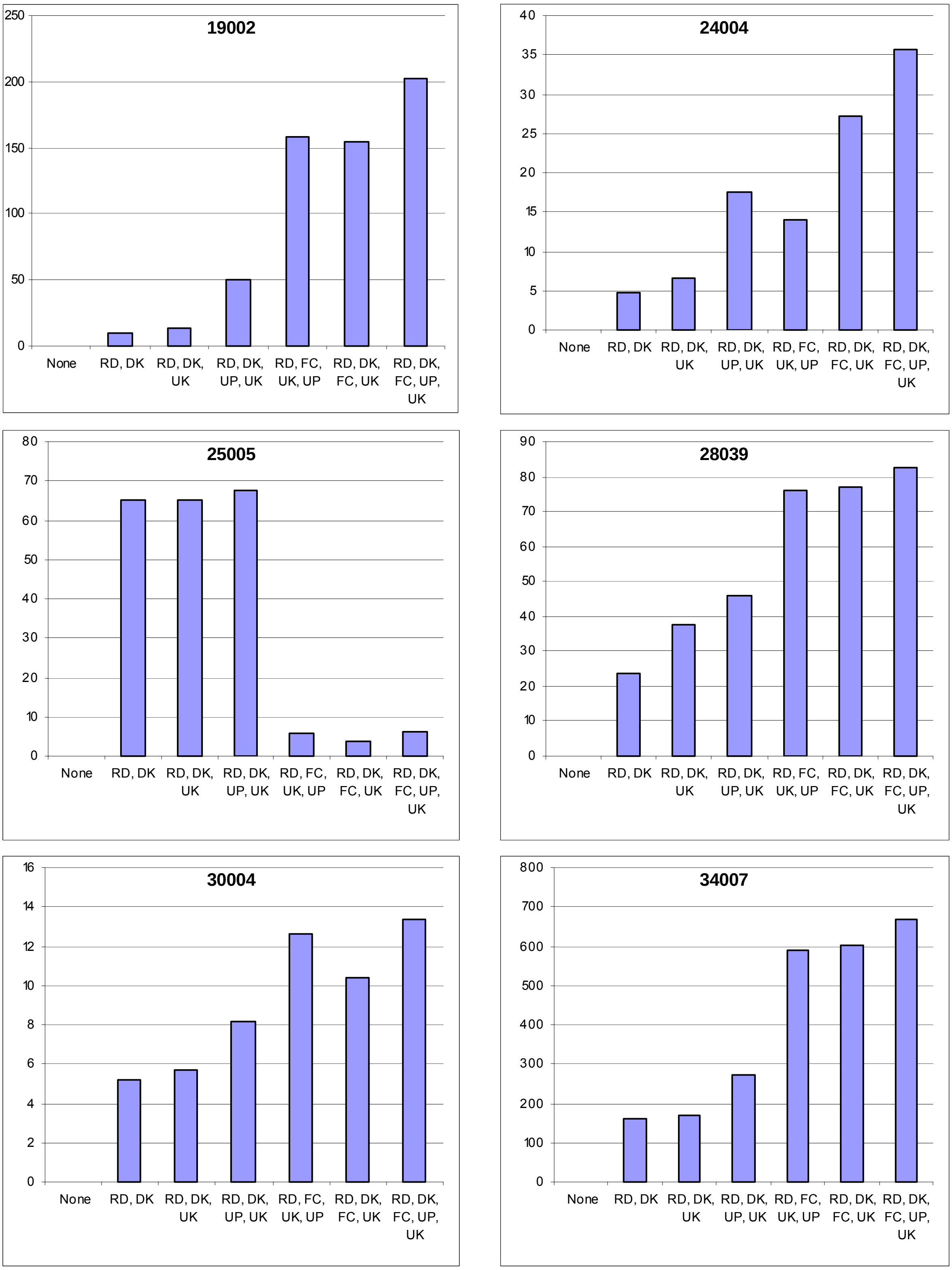


Figure 4.4 Sensitivity test showing percentage increase in MSE given a series of fixed parameters

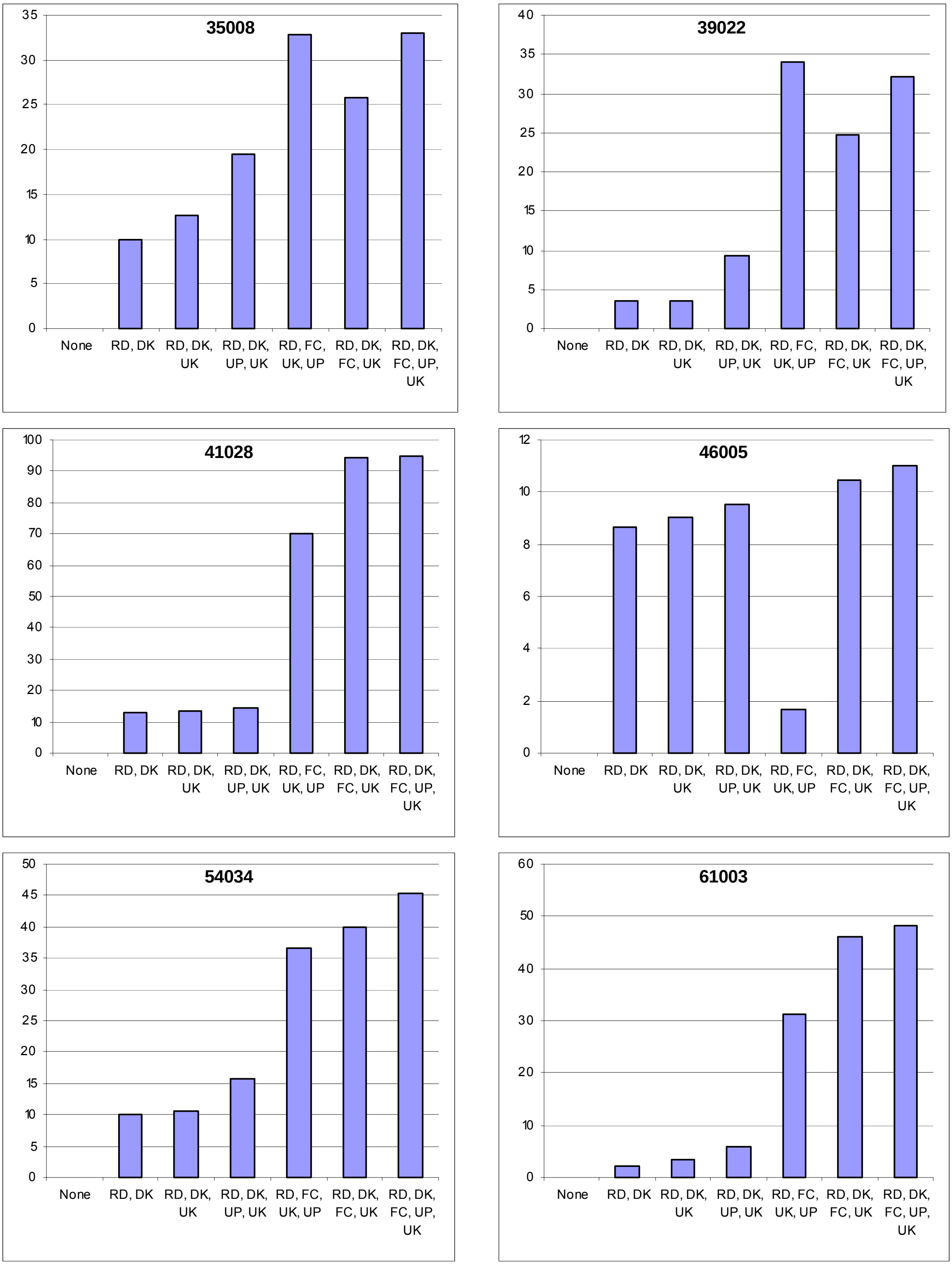


Figure 4.4 (contd) Sensitivity test showing percentage increase in MSE given a series of fixed parameters

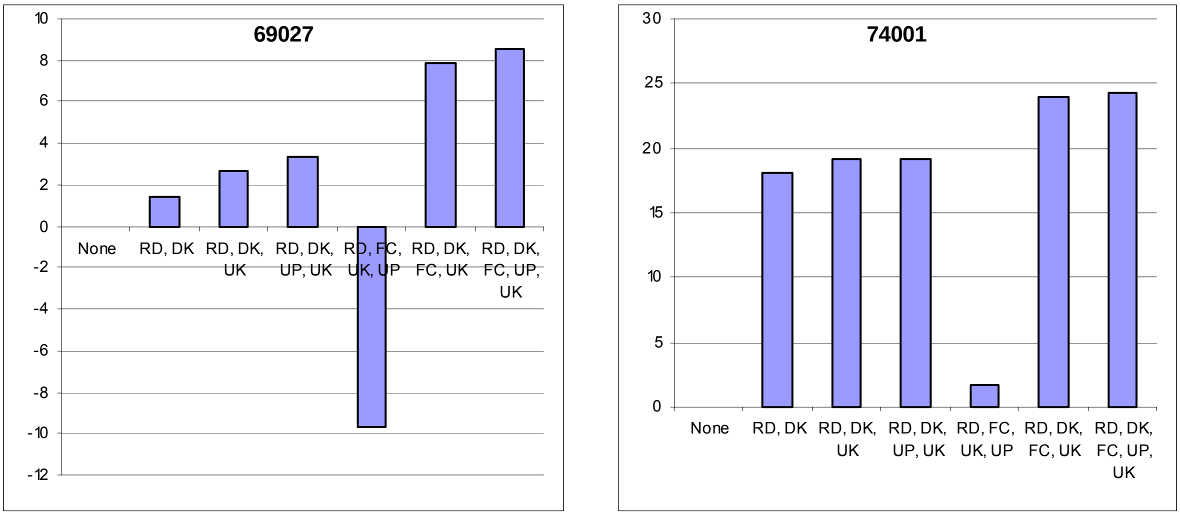


Figure 4.4 (contd) Sensitivity test showing percentage increase in MSE given a series of fixed parameters

4.4.2 Loss model

It was found that the *FC* parameter, when included as a free variable in the autocalibration, often converged towards unrealistically high values (*FC* > 500 mm) and, subsequently, it was decided to fix *FC* intelligently using results obtained using the DAYMOD model described in Section 3.2.4 and Appendix D. The *FC* parameter derived was fixed through a regression analysis linking the DAYMOD values to a set of catchment descriptors as

$$FC = 49.9\, PROPWET^{\,0.51} BFIHOST^{\,0.23} \tag{4.2}$$

where *PROPWET* and *BFIHOST* are readily available from the FEH CD-ROM (Bayliss, 1999). In most cases, using a fixed *FC* value does give a significant increase in MSE compared to fixing other parameters. This can be observed when comparing the percentage increase in MSE when moving from fixed {RD, DK, U_k} to fixed {RD, DK, U_k, FC} or from {RD, DK, U_k, UP} to {RD, DK, U_k, UP, FC}. Unfortunately, this rise is considered a necessary sacrifice in order to obtain a version of the ReFH model that can be generalised to any catchment.

As an alternative to the *FC* parameter it was investigated whether fixing *FC* and instead using *DK* as the free parameter in the loss model would produce benefits. Comparing bar number 3 (from left) {RD, DK, U_p, U_k} on the plots in Figure 4.4 with bar number 4 {RD, FC, U_p, U_k} it is clear that in most cases *FC* is a superior explanatory parameter than *DK* as judged by *MSE*. However, in some cases (catchments 69027 and 74001) a free *DK* parameter gives a significantly improved model performance compared to using *FC*. No reason for this apparent superiority of *DK* in these cases were identified and given the generally better performance of ReFH when using *FC* it was decided to keep a fixed *DK* value.

To investigate if the chosen *DK* value of 0.8 is appropriate, a ReFH model with two free parameters, i.e. fixed {*RD, DK, FC,* U_p, U_k } was recalibrated using a fixed value of *DK* = 0.4. The results, in terms of percentage increase of MSE compared to the case where no parameters are fixed, are shown in Table 4.2. A higher value of percentage increase indicates a reduced model performance.

Table 4.2 Comparing increase in MSE for *DK* = 0.4 and *DK* = 0.8 with fixed ReFH model structure.

Catchment	% increase of MSE		Catchment	% increase of MSE	
	DK=0.8	DK=0.4		RD=0.8	RD=0.4
19002	163	202	39022	34	32
24004	39	36	41028	83	95
25005	6	6	46005	3	11
28039	77	83	54034	37	45
30004	16	13	61003	32	48
34007	606	669	69027	-8	9
35008	34	33	74001	32	24

From the results in Table 4.2 it can be seen that changing the fixed value of *DK* has little impact on the performance of the ReFH model. Based on this investigation it was decided to keep the fixed value of *DK* = 0.8.

4.4.3 Routing model

Compared to the increase in *MSE* endured by fixing *FC*, the additional increase from fixing *Up* and *Uk* are considered less important as evident when comparing {*RD*, *DK*, U_p, U_k} to {*RD*, *DK*, *FC*, U_p, U_k}. Attempts to spatially generalise these two parameters from early calibrations of the entire data set (101 Catchments) found no or little relationship between U_p and U_k and catchment descriptors. Based on these findings it was decided to fix the values of U_p and U_k, i.e. the shape of the IUH described in Section 3.2.2 is fixed and only controlled by the Time to peak parameter. Values of U_p and U_k were obtained by applying the calibration procedure to the entire data set twice. Firstly, both U_p and U_k were allowed to be free parameters. From this data set an average value of U_k = 0.80 was obtained. The second comprehensive calibration was conducted with U_k fixed (as well as *RD, DK, FC*) and only U_p (as well as *Tp* and *SM*) varying freely. From this second comprehensive calibration, the average U_p value was found to be U_p = 0.65.

4.4.4 Final ReFH model structure

Fixing the two routing model parameters U_p (= 0.65) and U_k (= 0.80), the field capacity *FC (Section 4.2)*, the rooting depth *RD* (= 0.3) and the daily decay rate *DK* (= 0.8), the final structure of the ReFH model consists of two free parameters: the Time to peak (*Tp*) controlling the timing of the catchment response and the soil moisture scaling parameter (*SM*) controlling the soil moisture capacity of the catchment and, thereby, controlling the loss model. These two parameters are equivalent to the *Tp* and *SPR* parameters in the existing FSR/FEH model.

Combining the *FC* parameter (fixed using Equation 4.2) with *SM* as described in Section 3.2.4 gives the final loss model parameter C_{max} to be used in the remainder of this report.

4.5 Analysis of all events

4.5.1 General

Following on from the sensitivity analysis, the ReFH model parameters (*SM*, *Tp*, *BL*, *BR*) were estimated at every catchment with more than five observed flood events available of which at least one has a peak flow larger than QMED. From the updated Flood Event Archive, as described in Section 2, a total of 157 catchments complying with both of these requirements were identified. For each catchment the calibration procedure outlined in section 4.1 and section 4.2 was carried out. During the calibration, a total of 49 catchments were excluded from further analysis for a number of reasons listed below.

4.5.2 Missing baseflow information

The ReFH model requires the observed flood events to have a long recession in order to allow estimation of the two baseflow parameters, BL and BR, as described in section 4.2. Unfortunately, many of the observed flood events collected for use in the FSR (NERC, 1975) were compiled with little or no emphasis on the recession part of the hydrograph. As a result, a total of 16 catchments were excluded due to lack of sufficient baseflow information.

4.5.3 Missing daily rainfall

To estimate the initial soil moisture for each observed flood event, the ReFH model requires access to between one and two years of catchment average daily rainfall (CADR) leading up to the onset of the event to estimate initial soil moisture. However, for some catchments no CADR was available for the period from which the observed flood events originate. The problem was mainly found with catchments where the observed flood events were recorded in the 1960s and early 1970s. A total of 14 catchments were excluded due to lack of CADR.

4.5.4 Missing catchment descriptors

For each catchment it is important that a set of catchment descriptors are available from the FEH CD-ROM. However, for reasons listed by Bayliss (1999), the DTM used to calculate the catchment descriptors does not give a sufficiently accurate delineation of the catchment boundary. Four catchments were found not to have catchment descriptor information and, subsequently, were excluded from the analysis.

4.5.5 ReFH modelling issues

The ReFH model was developed as a relatively simple deterministic lumped conceptual flood event model and constitutes a mathematical formulation of the major conceptual catchment processes, i.e. loss, routing and baseflow generation. However, applying a relatively simple hydrological model to data from a large number of real catchments it is to be expected that the model will not perform equally well on all catchments. A number of reasons for poor performance can be listed such as poor data quality or local effects not included in a generic model structure. In such cases the model cannot be expected to perform well and the onus is on the analyst to identify such cases. A more serious matter arises if the generic model structure is found unable to model flood events in certain types of catchments, in which case the significance of the problem should be balanced against the resources required for further model development and testing. For a total of 22 catchments, the ReFH model was found not to perform well enough to be included in the final sample. For some catchments it was identified as a data problem, but identification of unrealistically large values of the loss model parameter of SM > 9, and sometimes SM > 30, were identified in baseflow dominated catchments.

4.5.6 Final sample of catchments

The final sample of catchments complying with the rule concerning availability of observed events (minimum of five events of which at least one has a peak flow value exceeding QMED) and for which the ReFH model has been calibrated successfully consists of 101 catchments. The ReFH parameter values for these catchments are listed in Appendix F and the location of the gauges are shown in Figure 4.5.

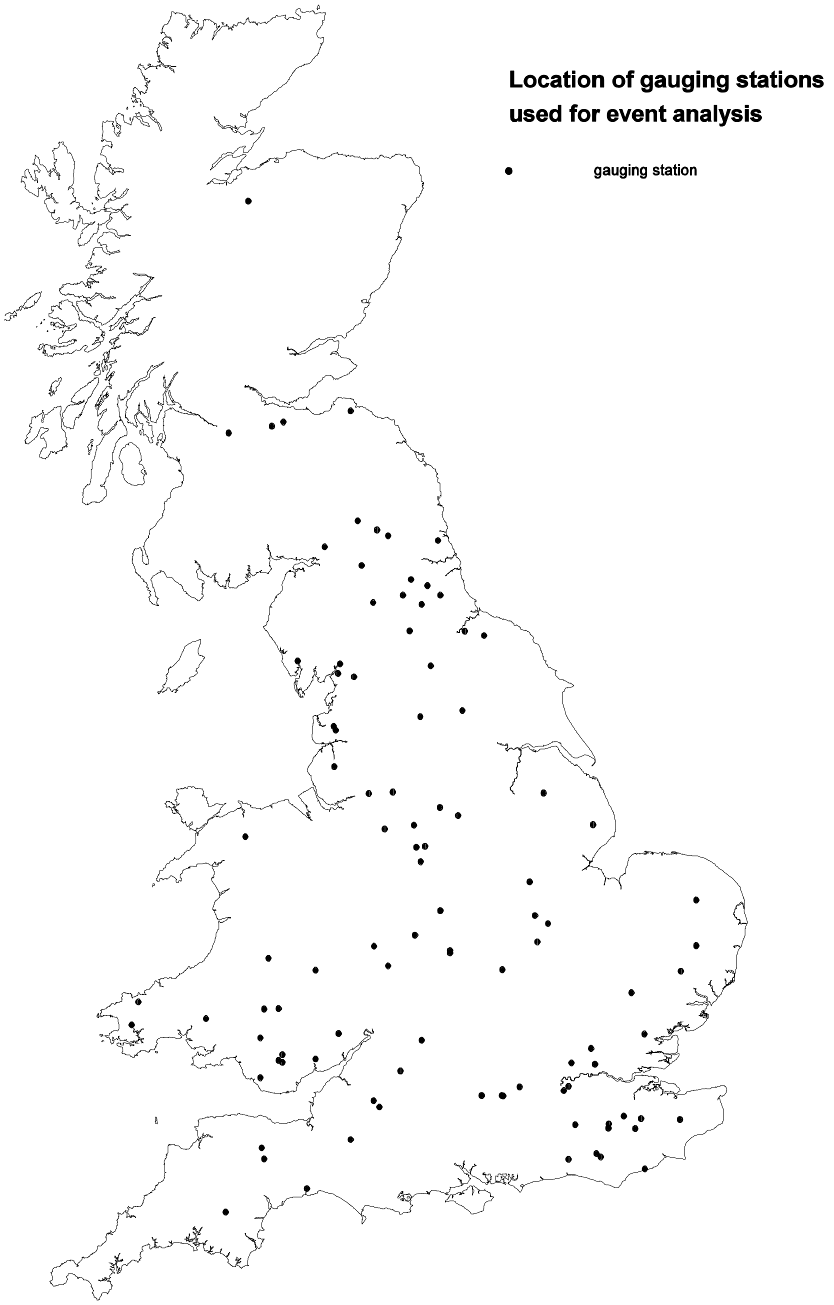


Figure 4.5 Locations of gauging stations where the ReFH model has been calibrated.

The map in Figure 4.5 shows a reasonable geographical spread of the catchment with ReFH calibration results, although there are few stations with suitable data in the northern parts of Wales or much of Scotland.

4.6 Examples

The parameter estimation procedure applied to each catchment is illustrated using data from three different gauging station. For each catchment, the two baseflow parameters *BL* and *BR* are the first two to be estimated for each of the available events as described in Section 4.2. Next, the optimisation scheme described in Section 4.1 is applied to estimate the two remaining model parameters (C_{max}, *Tp*). Model performance is inspected by visual comparison of observed and simulated flow.

25005 River Leven at Leven Bridge

This is an essentially rural catchment (*URBEXT*=0.010) with a contributing catchment area of 195 km^2 as derived from the IHDTM, and with annual average rainfall of 726mm and a *SPRHOST* value of 40.5%. A total of 15 flood events of sufficiently good quality are available. The time period covered by the flood events in Table 4.1 is from 1978 to 1983. For three of the 15 events the hydrograph recession was found to be too short to give realistic estimates of *BL* and *BR*. The estimated baseflow parameters for each event and the average values for the catchment are shown in Table 4.3.

Table 4.3 Baseflow parameters for catchment 25005

Event	*BL*	*BR*	Event	*BL*	*BR*
05 Aug 78	42.21	0.69	26 Apr 83	66.55	0.61
12 Dec 78	62.20	1.38	08 Dec 83	58.96	0.47
19 May 79	36.75	1.05	05 Jan 88	84.58	1.18
29 May 79	28.99	1.07	03 Dec 81	63.01	1.92
14 Nov 79	59.81	0.70	20 Apr 83	37.56	0.77
11 Mar 80	104.19	1.28	01 Jun 83	*	*
17 Mar 80	*	*	03 Feb 88	*	*
29 Nov 81	76.26	1.01			
			Average	60.09	1.01

* Recession too short to estimate *BL* and BR

The other ReFH parameters were estimated using all events in Table 4.3, including the events not used for estimating the two baseflow parameters. The resulting model plots are shown in Figure 4.6. Catchment average daily rainfall for catchment 25005 is available for the period 1961-2000, i.e. no problems deriving the initial soil moisture content (C_{ini}) for each event using the daily soil moisture accounting model.

On the individual modelling figures, the observed flow is plotted together with the total flow as derived by the ReFH model as well as the contribution from the baseflow model. Also, in the upper right corner of each figure is plotted the shape of the unit-hydrograph after conversion of the IUH to a unit-hydrograph of the correct time step using the S-curve technique.

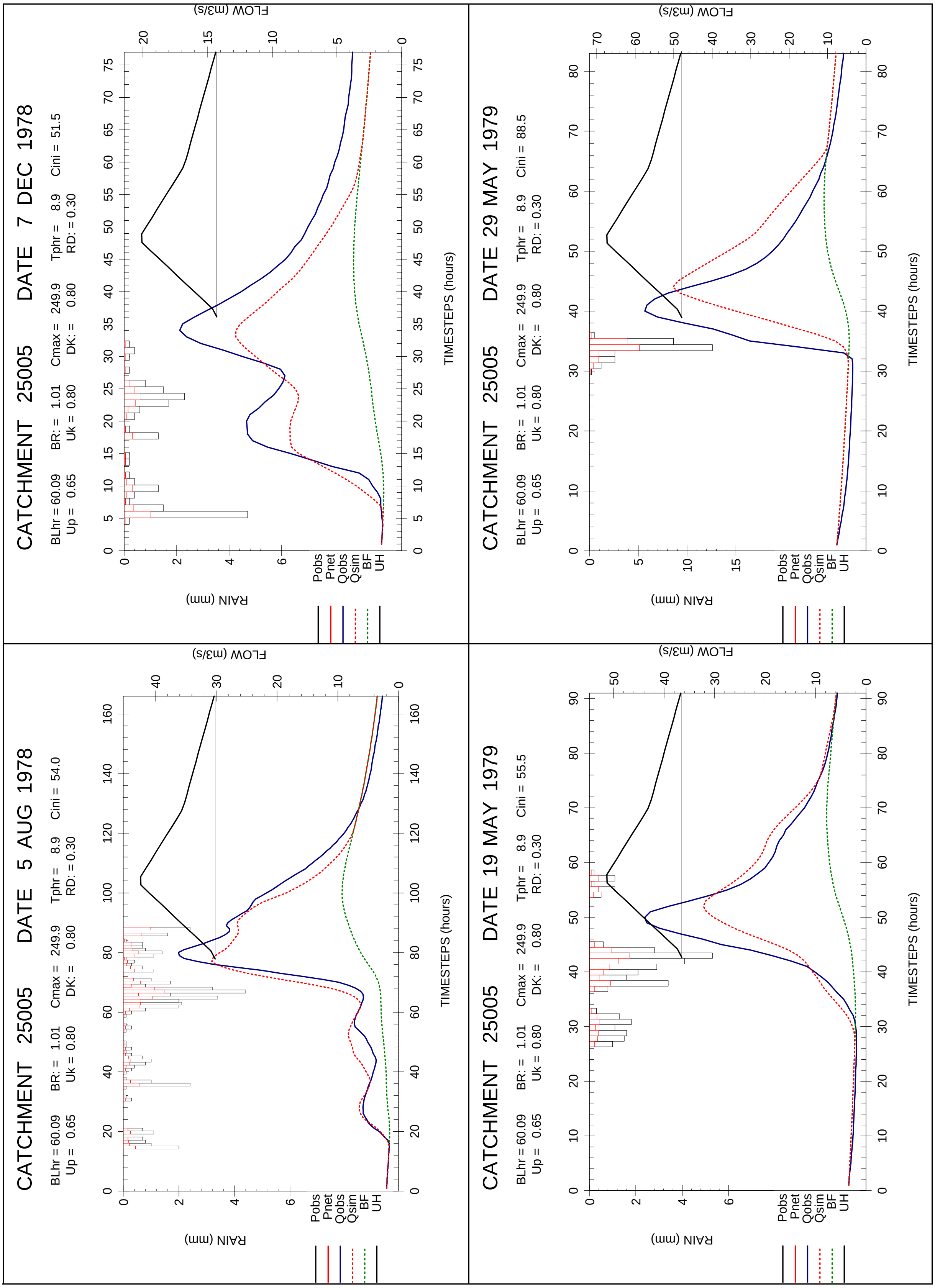


Figure 4.6 ReFH model fits for catchment 25005.

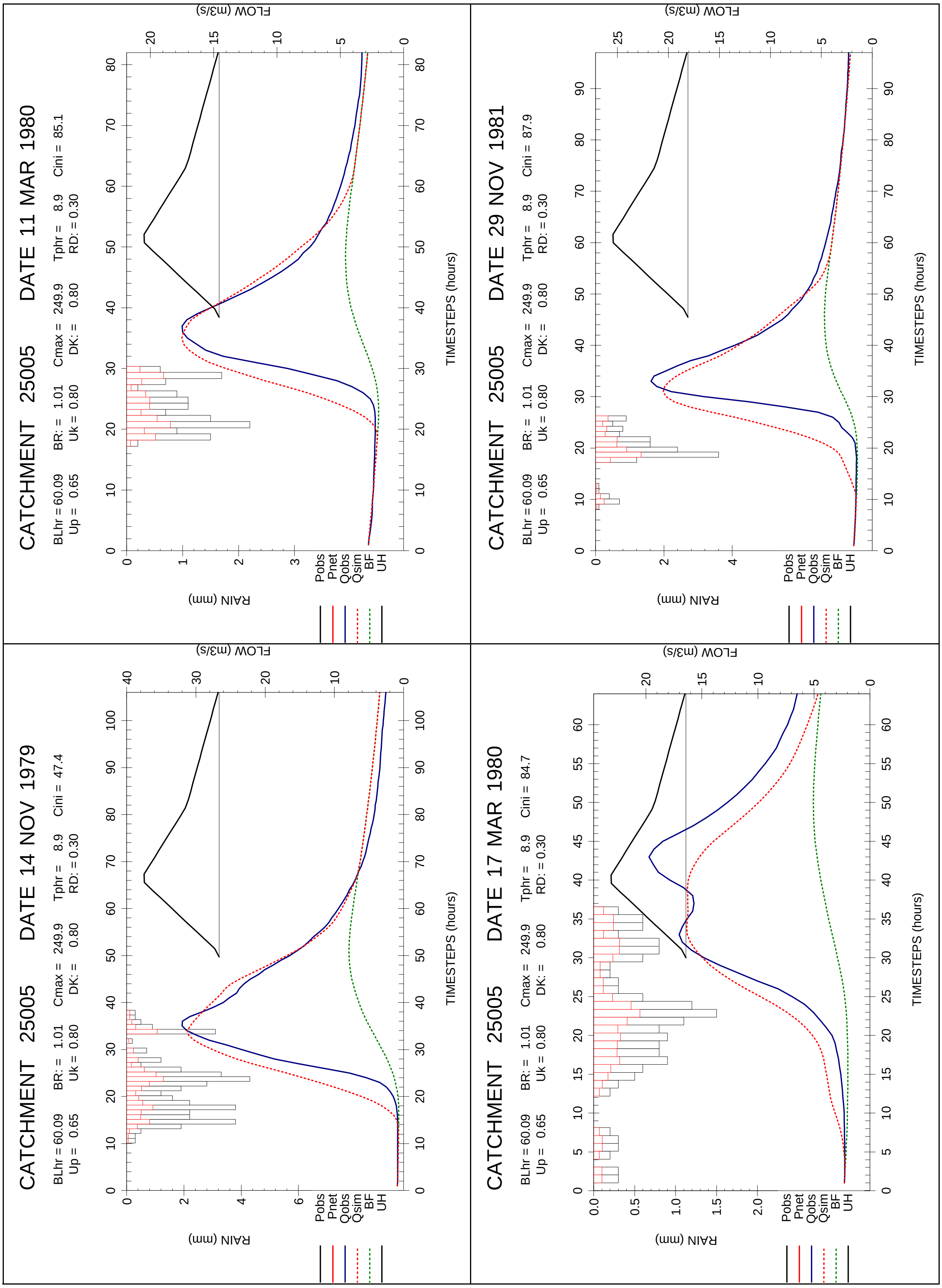


Figure 4.6 (contd) ReFH model fits for catchment 25005.

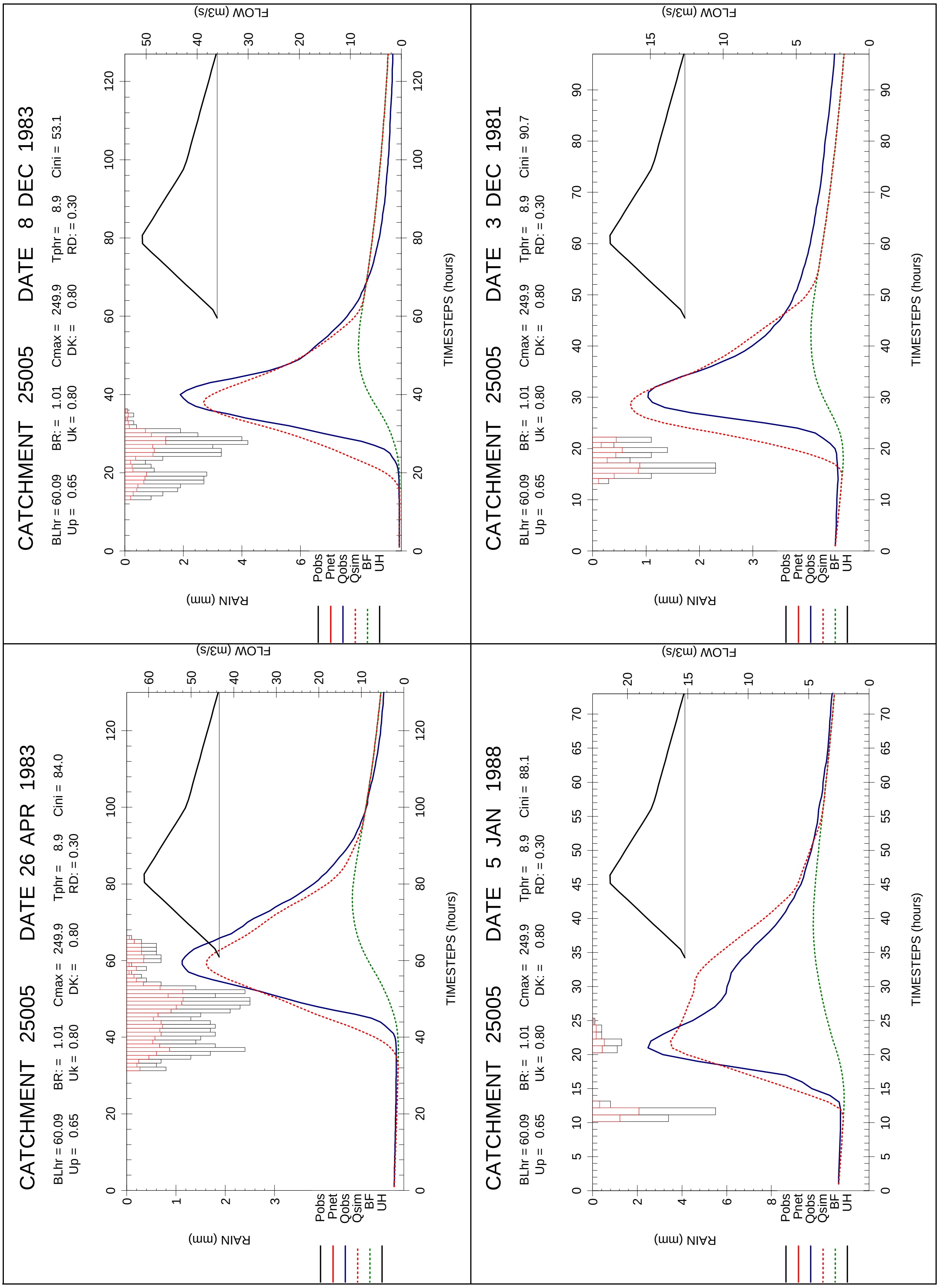


Figure 4.6 (contd) ReFH model fits for catchment 25005.

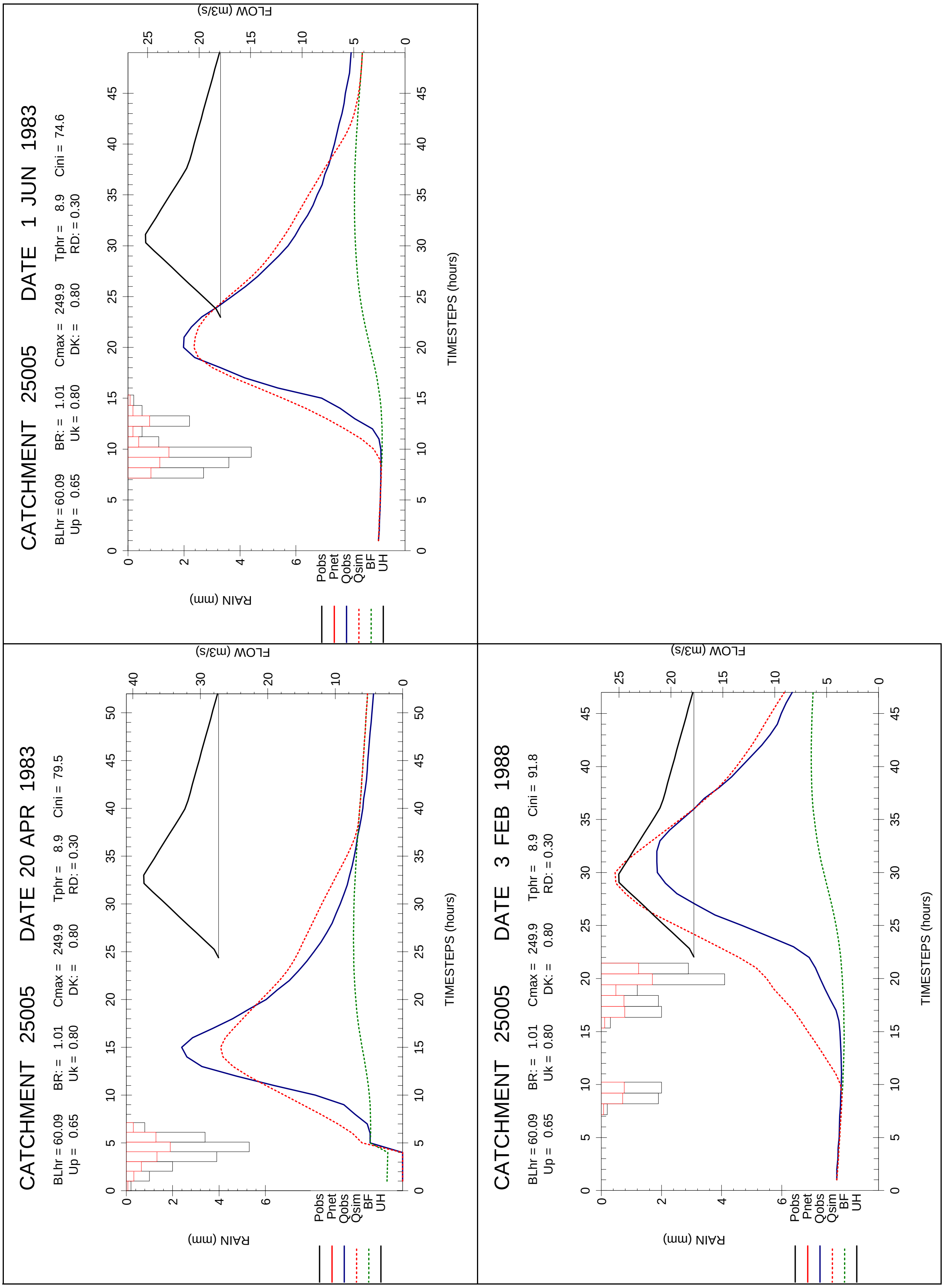


Figure 4.6 (contd) ReFH model fits for catchment 25005.

From the comparison between observed and modelled flow in Figure 4.6 it can be observed that all 15 events have been modelled using identical model parameters and that the modelled and observed flow generally corresponds well. Using a baseflow model with catchment average parameters appears to give sensible baseflow simulations for all events, including the three events (17 Mar 80, 1 Jan 83 and 3 Feb 88) deemed to have too short hydrograph recessions for proper estimation of baseflow parameters.

57005 Taff at Pontypridd

This slightly urbanised (*URBEXT* = 0.040) catchment is located in southern Wales and covers an area of 454.8 km^2. The average annual rainfall is 1832 mm. A series of reservoirs, notably the Llwŷn-on and the Taf Fechan reservoirs are located in the upper part of the catchment, reducing *FARL* to a value of 0.951. A total of 16 good quality flood events were available for this catchment. However, of the 16 events, only six were considered to have a sufficiently long recession for reliable estimation of the base flow parameters. The estimated baseflow parameters are shown in Table 4.4.

Table 4.4 Baseflow parameters for catchment 57005

Event	*BL*	BR	Event	*BL*	BR
22 Mar 68	*	*	05 Dec 72	*	*
26 Jan 68	*	*	05 Feb 90	40.34	1.04
10 Oct 68	*	*	31 Dec 90	*	*
26 Oct 68	*	*	01 Dec 92	27.91	1.29
17 Jan 69	78.39	3.26	09 Jan 92	94.52	3.39
11 Nov 69	*	*	17 Dec 93	97.89	1.89
15 Jan 70	*	*	26 Dec 94	*	*
01 Nov 70	*	*			
18 Oct 71	48.95	1.13	**Average**	64.67	2.00

* Recession too short to estimate *BL* and BR

The relatively few events used for estimation of the baseflow values combined with the variability in the estimated values of *BL* and BR result in the estimated average baseflow parameters to be associated with a large uncertainty. Next, the *Tp* and C_{max} parameters are estimated using the optimisation routine and the resulting modelling results, including parameter estimates, are shown in Figure 4.7.

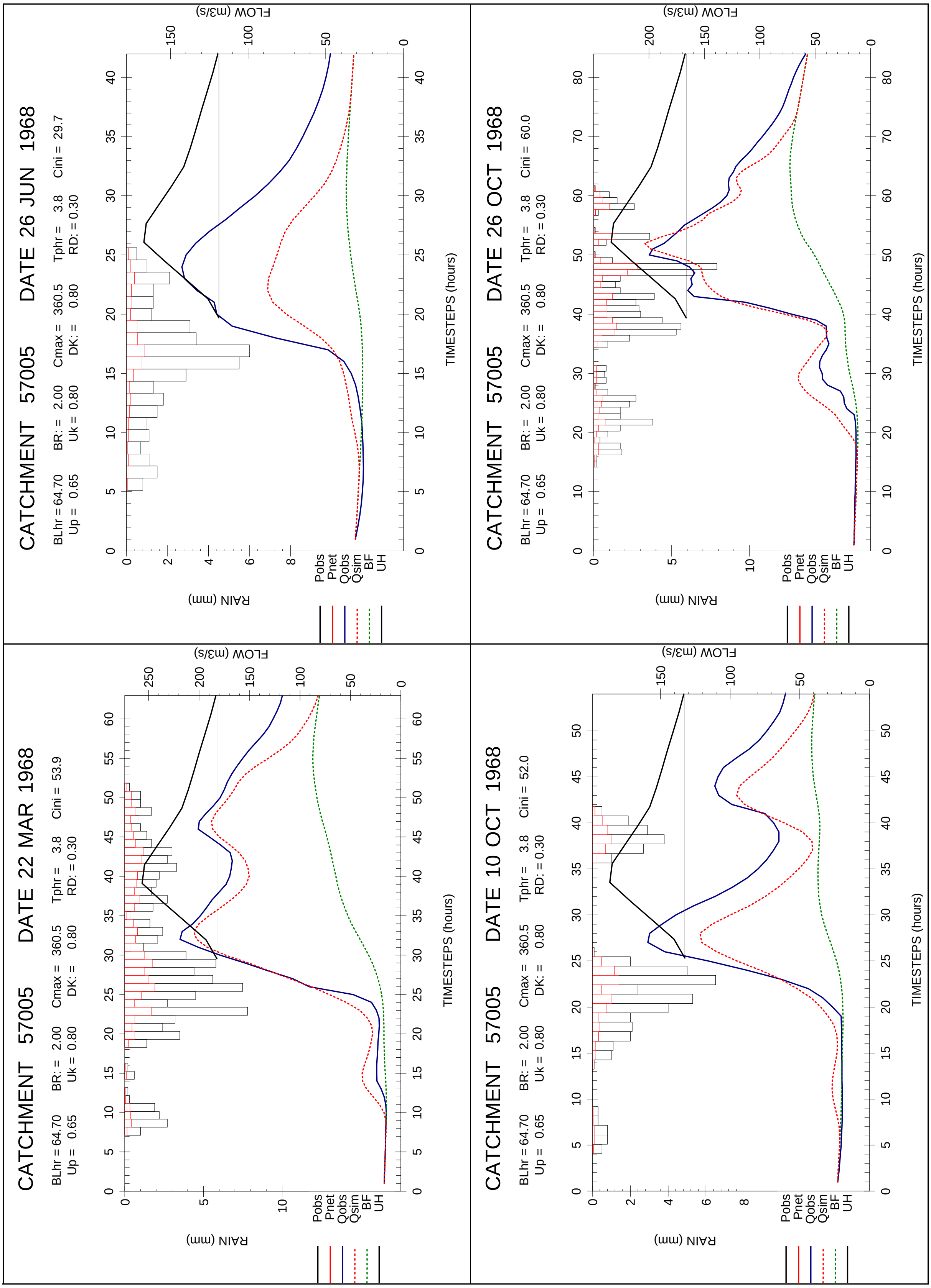


Figure 4.7 ReFH model fits for catchment 57005.

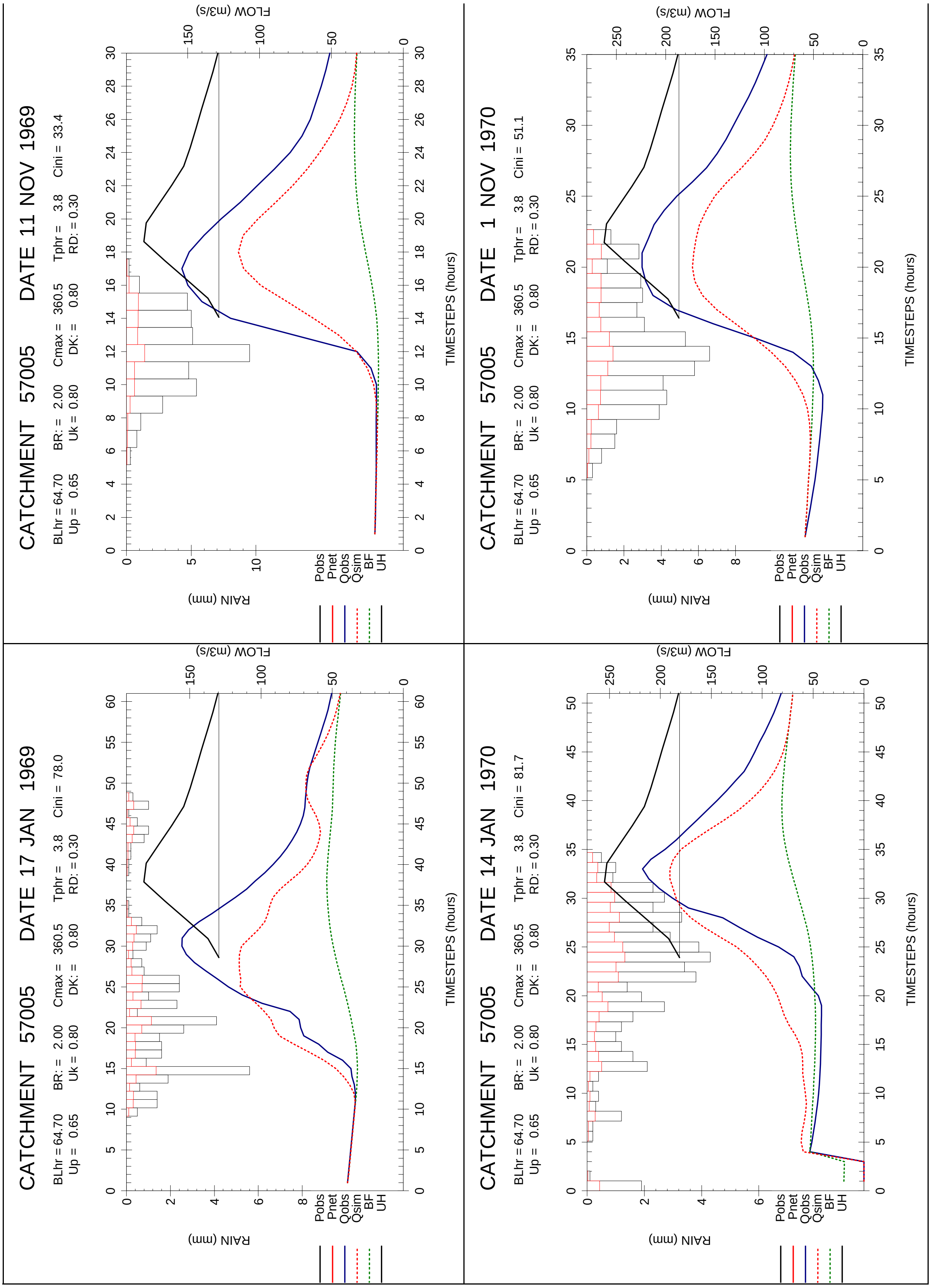


Figure 4.7 (contd) ReFH model fits for catchment 57005.

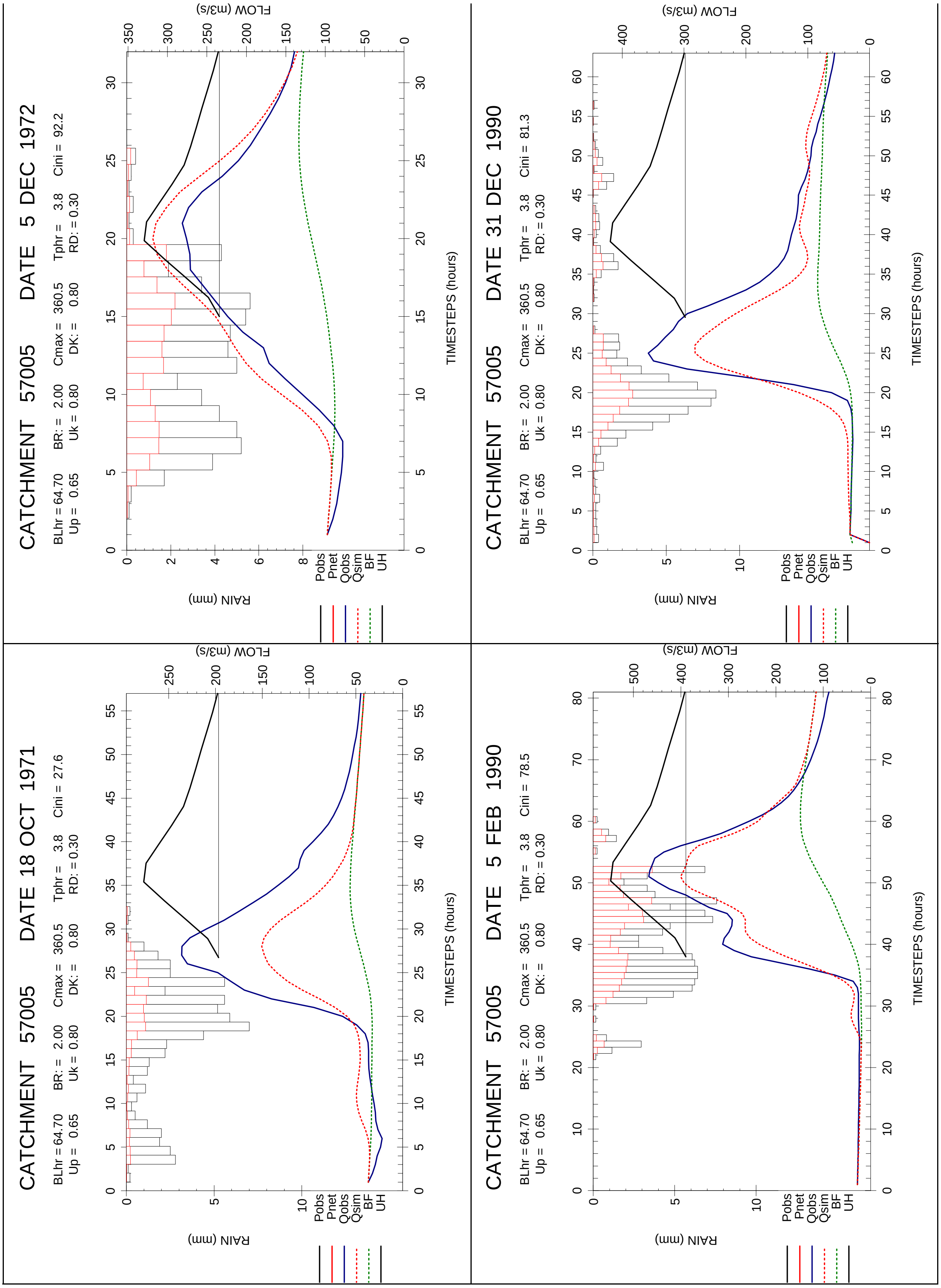


Figure 4.7 (contd) ReFH model fits for catchment 57005.

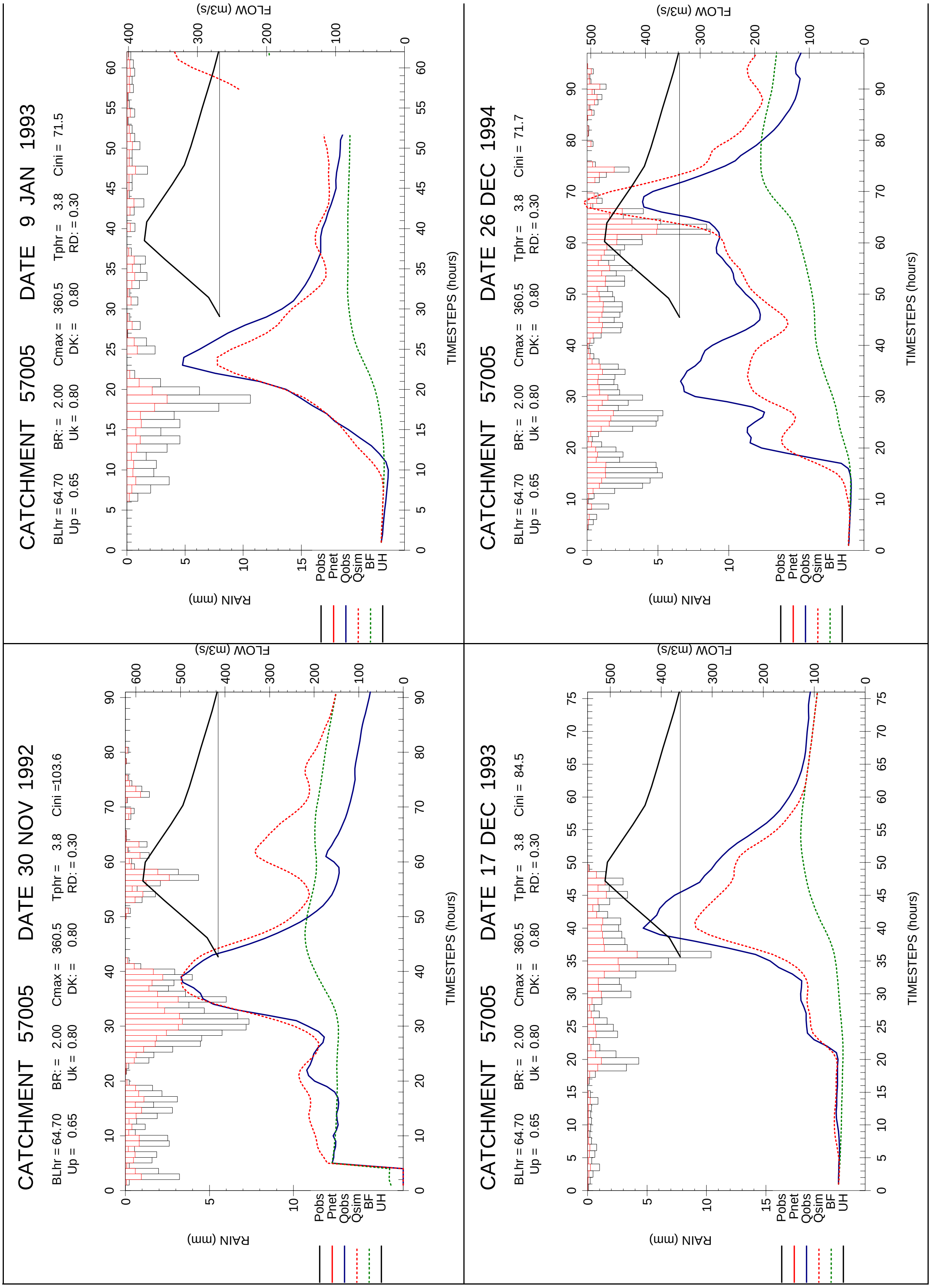


Figure 4.7 (contd) ReFH model fits for catchment 57005.

Compared to the previous catchment (25005) the ReFH model appears to perform less well on this catchment, even though the largest events are generally captured well. The events where the model performs particularly poorly (22 Mar 68, 11 Nov 69 and 18 Oct 71) are all characterised by having very low antecedent soil moisture content.

36010 Bumpstead Brook at Broad Green

With a catchment area of 28 km^2 this is a relatively small essentially rural (*URBEXT* = 0.0055) catchment located in the eastern part of England. The average annual rainfall is 588 mm, which is relatively low and the *SPRHOST* value is 44.6%. A total of 13 good quality flood events are available for this catchment. Only two of these events were considered to have too short a recession for reliable estimation of the baseflow parameters. The estimated baseflow parameters for each event and the average values for the catchment are shown in Table 4.5.

Table 4.5 Baseflow parameters for catchment 36010

Event	*BL*	BR	Event	*BL*	BR
20 Jan 85	40.45	0.38	01 Feb 94	57.75	0.59
01 Apr 87	57.06	0.63	26 Dec 94	37.48	1.10
18 Jan 87	25.48	0.50	20 Jan 95	39.36	0.41
28 Jul 87	38.24	0.41	24 Jan 95	*	*
10 Nov 87	*	*	31 Jan 95	48.98	0.67
04 Jan 88	88.14	0.43	07 Mar 95	55.86	0.55
20 Mar 88	62.69	0.90			
			Average	50.14	0.60

* Recession too short to estimate *BL* and BR

Next, the *Tp* and C_{max} parameters are estimated using the optimisation procedure outlined in Section 4.1. The catchment average daily rainfall used to obtain the initial soil moisture content was calculated using an extended area around the catchment in order to include sufficient gauges, i.e. less accurate estimates of C_{ini} must be expected. The resulting model plots are shown in Figure 4.8.

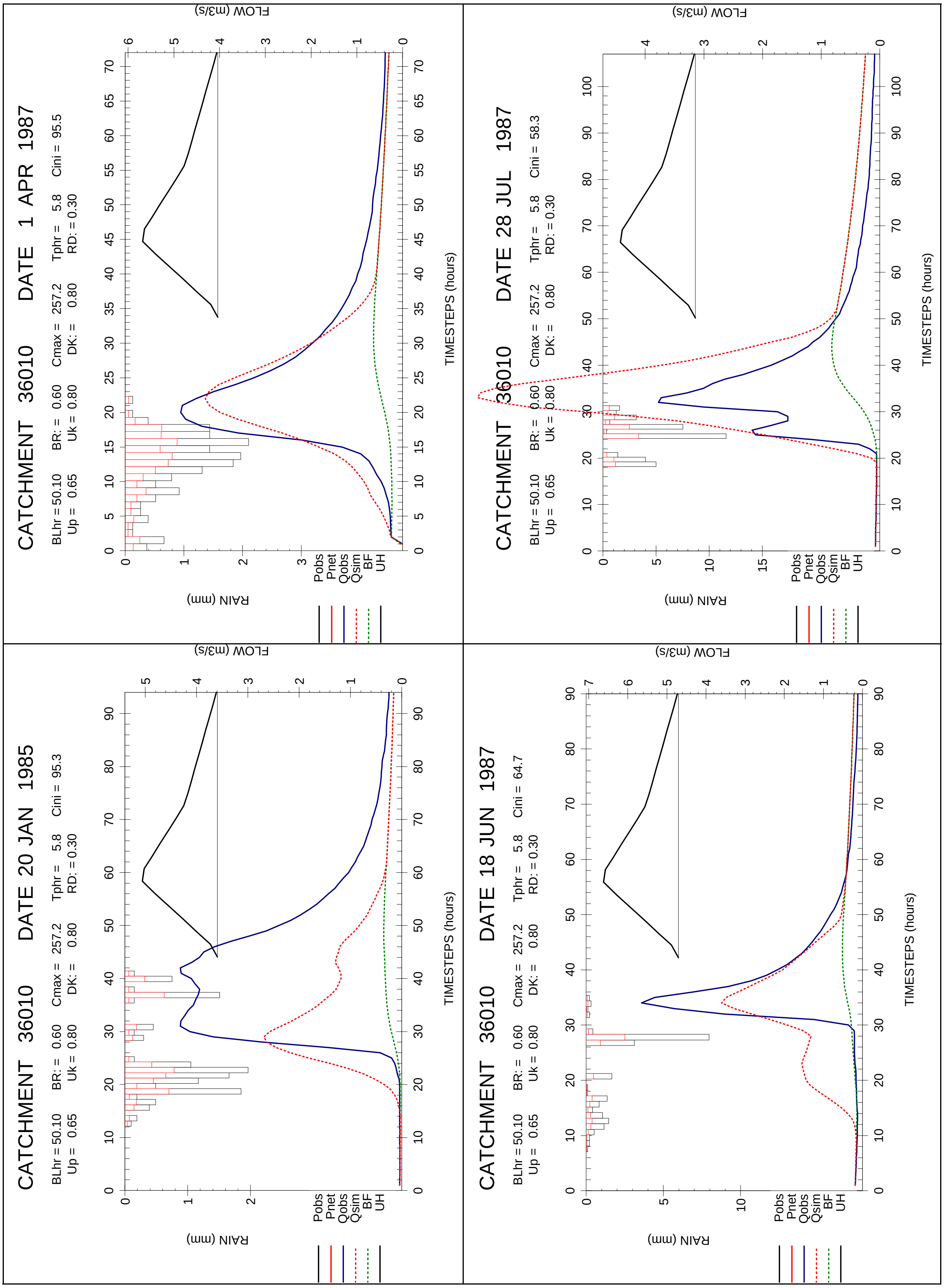


Figure 4.8 ReFH model fits for catchment 36010.

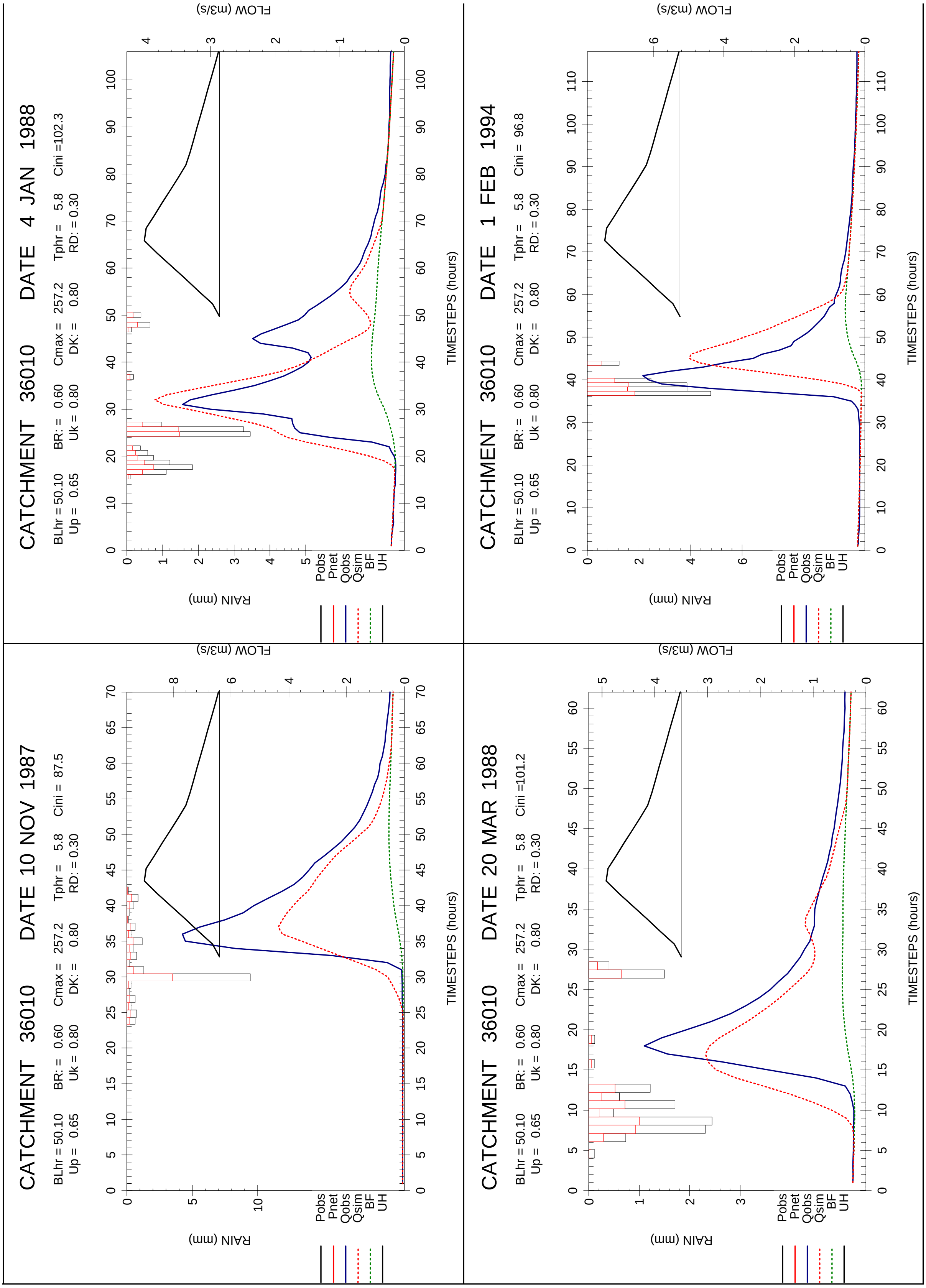


Figure 4.8 (contd) ReFH model fits for catchment 36010.

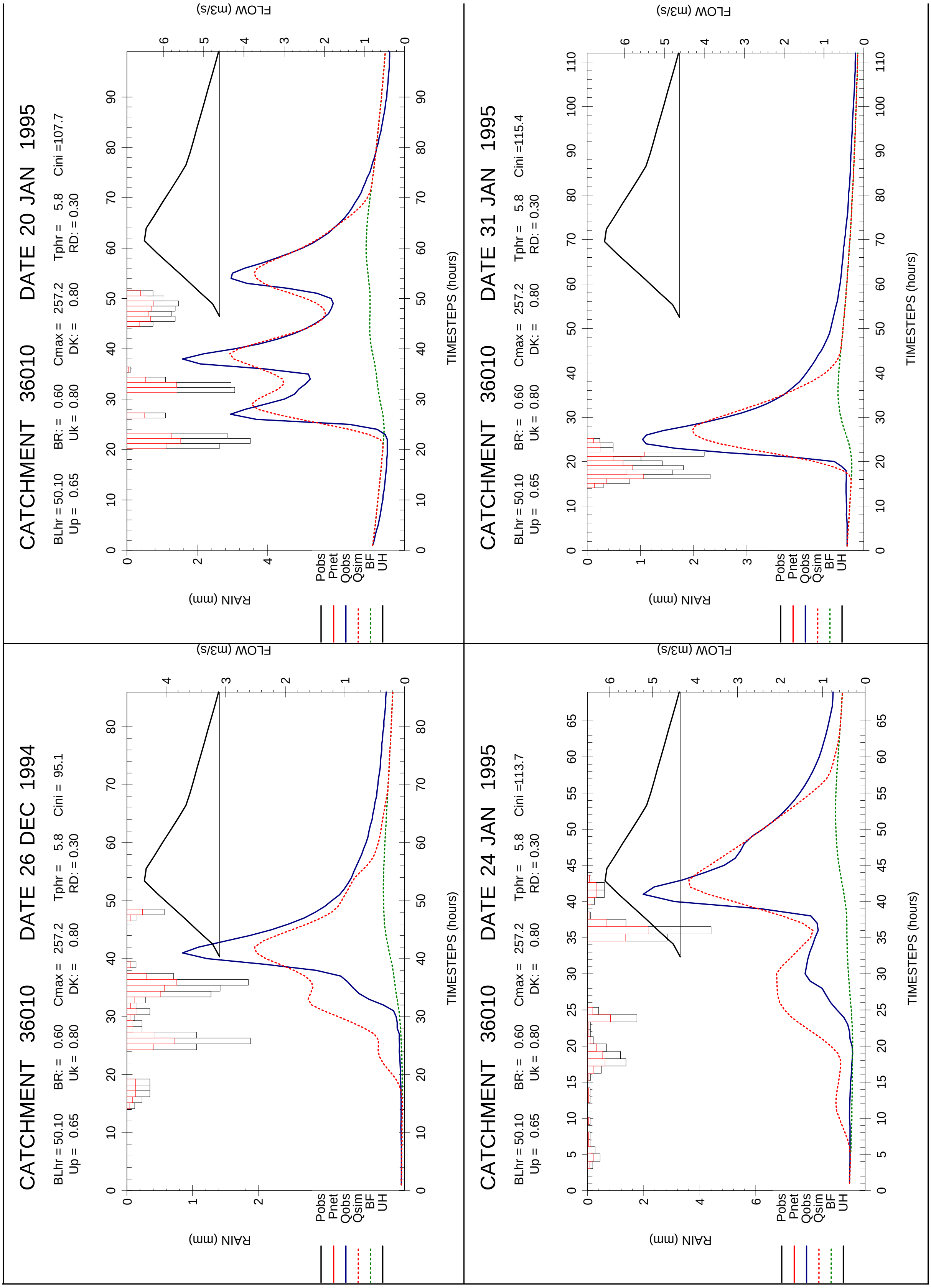


Figure 4.8 (contd) ReFH model fits for catchment 36010.

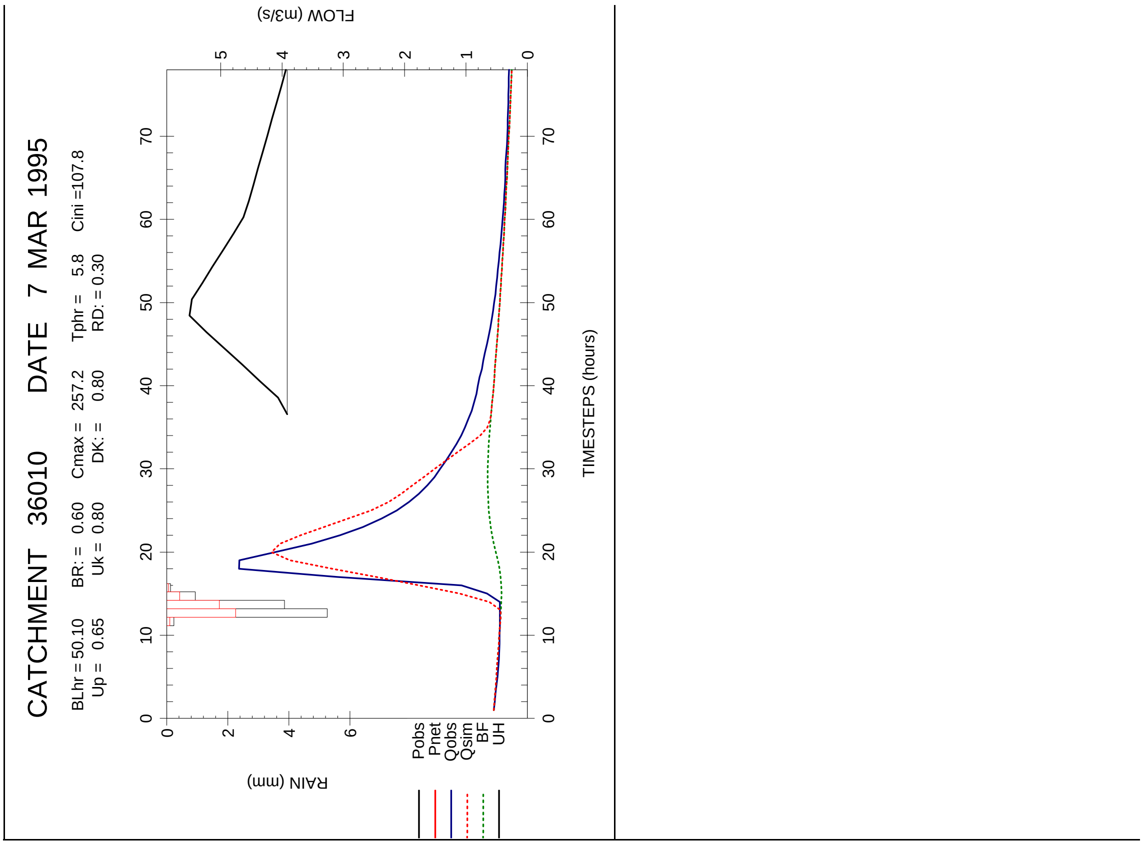


Figure 4.8 (contd) ReFH model fits for catchment 36010.

In general, the ReFH model performs well on this catchment and both under and overestimation of peak flow is present.

4.7 Analysis of the largest events

A study of the relationship between storm severity and catchment response time, as characterised through the Tp parameter, was conducted as part of the Flood Studies Report (NERC, 1975). The FSR team (I.6.5.3) studied variations of the Tp parameter with mean rainfall intensity for five catchments and concluded that no relationship could be identified with a reasonable degree of certainty. The FSR report refers to a similar investigation carried out in South Africa (Pullen, 1969), which came to the same conclusion. Though the FSR report concluded that, considering the data on the whole, no relationship between catchment response time and rainfall intensity could be identified, it was recognised that in the most extreme events response runoff does concentrate more quickly than usual and quoted the Louth (1920), Lynmouth (1952) and Bowland (1967) floods as examples.

Further investigations of relationships between flood magnitude and catchment response times were conducted by Jin (1993) and Ashfaq and Webster (2000) through analysis of observed events. Both studies concluded that catchment response time might decrease with increasing flood magnitude but also, in general, the data exhibited too much variation between events to offer conclusive evidence. The data analysed by Ashfaq and Webster (2000) consist mainly of flood events with a peak flow magnitude below mean annual maximum flood (QBAR), i.e. return periods below 2.33 years, making interference about the behaviour of flood with a return period of 100 years very uncertain. No information concerning the magnitude of the flood events analysed by Jin (1993) was reported.

As part of this study, the Flood Event Archive used by both the FSR and Ashfaq and Webster (2000) has been updated by adding a number of more recent and relatively large events (see Chapter 2). To further investigate the relationship between event magnitude and catchment response time, the available events with a flood peak magnitude larger than a 25-year event (as derived from a pooled analysis of AMAX series at each catchment, see Chapter 7 for further details) were identified and analysed. A total of 20 events out of the 1235 in the main analysis were found to exceed the 25-year threshold and the details of each event are shown in Table 4.6.

Table 4.6 Largest 20 flood events available

No.	River	Gauging station	Date	Peak flow (m^3s^{-1})	Return period (years)*	Tp event (hours)	Tp average (hours)	Tp ratio
22006	Blyth	Hartford Bridge	1-Apr 1992	163	146	8.22	8.82	0.93
25019	Leven	Easby	26-Aug 1987	16	90	2.96	3.64	0.81
27001	Nidd	Hunsingore Weir	16-Oct 1967	274	45	7.04	6.76	1.04
27001	Nidd	Hunsingore Weir	11-Sep 1968	304	78	5.21	6.76	0.77
27034	Ure	Kilgram Bridge	22-Mar 1968	379	25	6.44	5.98	1.08
28046	Dove	Izaak Walton	23-Oct 1998	27	27	5.58	6.33	0.88
31005	Welland	Tixover	8-Mar 1975	107	94	21.32	24.47	0.87
34007	Dove	Oakly Park	15-Sep 1968	38	59	14.2	14.7	0.97
38020	Cobbins Brook	Seawardstone Road	13-Oct 1993	20	47	6.73	5.82	1.16
39053	Mole	Horley	15-Sep 1968	63	50	5.67	5.59	1.01
40006	Bourne	Hadlow	15-Sep 1968	55	3505	3.39	3.87	0.88
41005	Ouse	Gold Bridge	12-Oct 2000	98	158	6.82	9.93	0.69
41006	Uck	Isfield Weir	12-Oct 2000	132	182	4.51	5.63	0.80
45004	Axe	Whitford	9-Jul 1968	218	61	4.89	6.61	0.74
53008	Avon	Great Somerford	9-Jul 1968	105	303	9.62	9.81	0.98
54019	Avon	Stareton	9-Jul 1968	99	90	22.11	24.7	0.90
55026	Wye	Ddol Farm	5-Aug 1973	252	79	3.68	3.76	0.98
68006	Dane	Hulme Walfield	8-May 1965	93	28	3.6	3.21	1.12
68006	Dane	Hulme Walfield	8-Sep 1965	123	138	3.16	3.21	0.98
68006	Dane	Hulme Walfield	8-Dec 1965	105	55	1.61	3.21	0.50

* Return period derived by comparing peak flow to flood frequency curve derived using pooled statistical analysis (Section 7.6).

The output from the parameter calibration method (Section 4.1) developed in this study is a set of single catchment average parameters (C_{max} and *Tp*) based on optimisation over several events. As a result, parameter values have not in general been discussed for each individual event. This is a departure from the approach of the FSR where each flood event was analysed in turn and a catchment value subsequently obtained as an average of the individual parameters of each event.

However, to assess the catchment response times of the largest events to the catchment average response times, the ReFH model parameters were estimated by considering each of the events in Table 4.6 on an individual basis in the optimisation procedure. The ratio between the *Tp* of the large event and the catchment average *Tp* are reported in Table 4.6 and plotted in Figure 4.9 against return period.

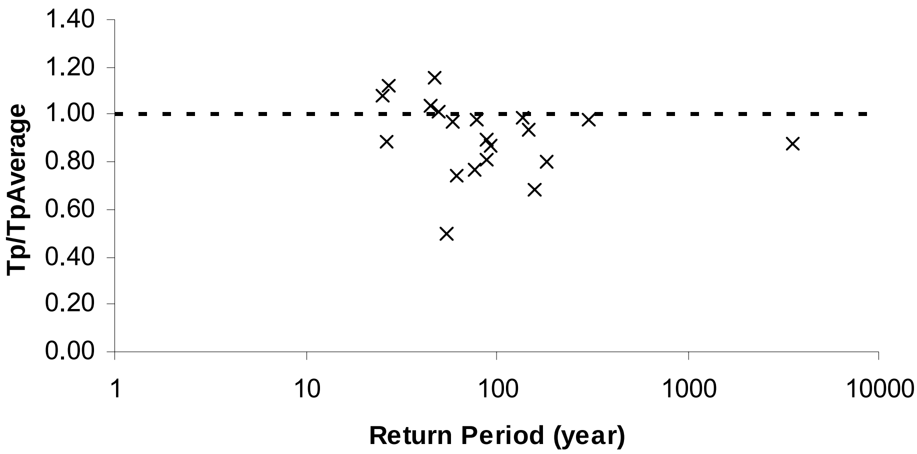


Figure 4.9 Ratio between *Tp* for large event and catchment average *Tp*

From Figure 4.9 it can be observed that the ratio is generally less than one, i.e. faster catchment response from large events, but no consistent relationship can reasonably be identified between response time and event rarity. The plot might be disturbed by the 1968 event on the river Bourne, which has been associated with a very large return period. In Figure 4.10 the data have been re-plotted with this particular event removed from the data set.

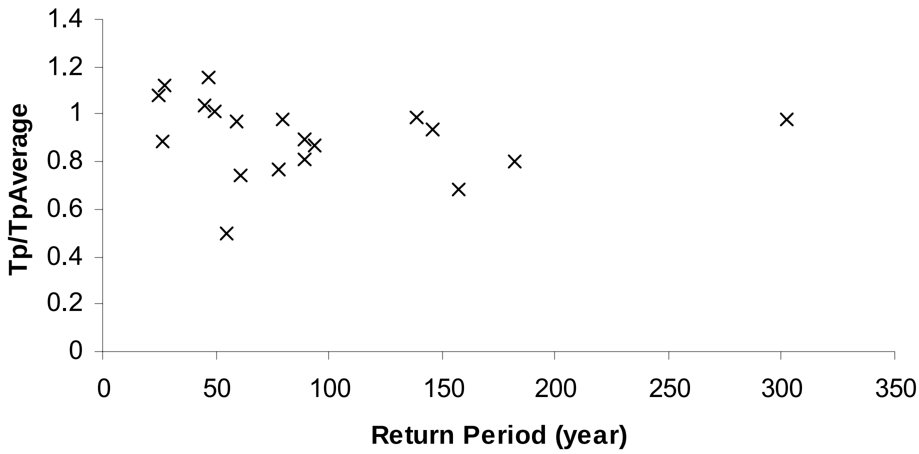


Figure 4.10 Ratio between *Tp* for large event and catchment average *Tp* (excluding the 1968 event on River Bourne)

The variation in the available data was considered too large for developing a relationship between *Tp* and event rarity to be used in a generic procedure for design flood estimation in the UK. However, this investigation does support the finding of previous studies that catchment response time decreases when considering large events. It is recommended that further data collection and research is undertaken before this mechanism is sufficiently well understood to be implemented in a design procedure.

5. Design rainfall inputs to the revitalised rainfall-runoff method

This chapter introduces the design rainfall model used for calibration of the method for design flood computation in the revitalised FSR/FEH rainfall-runoff method. In Chapter 6 the design input specified in this chapter will be used to derive the design values of initial soil moisture content (C_{ini}) and to carry out the final calibration of the ReFH design model.

5.1 Introduction

A criticism often voiced in connection with the FSR/FEH Rainfall-Runoff design method concerns the combination of design storms derived from annual maximum storms (commonly encountered during the dry summer) with soil conditions prevailing during the wet winter period (where most flood events on rural catchments are observed). A combination of high summer rainfall on wet winter catchments will result in design floods of excessive magnitude. Though the calibration of the FSR design model ensured floods of a correct magnitude, the lack of physical representation of the seasonal flood mechanisms reduces the confidence in the calibration, especially when the model is applied outside the scope of the calibration

In this study, the consideration of seasonality in the major flood generating mechanisms has been given a more prominent position than in the FSR in order to reduce the problem described above. The development of the design model has been carried out by considering two seasons: winter (November - April) and summer (May - October). For each season a set of design input variables will be specified, including design rainfall, initial soil moisture and initial baseflow, allowing for the model to produce seasonal design floods. The profiles of the design rainfall hyetographs are maintained in the form presented in the FSR/FEH method.

5.2 Design rainfall depth

As part of the FEH (IH, 1999), a spatially generalised DDF model was developed, enabling estimation of design rainfall with durations between 30min and 8days at any site in the UK. The DDF model was developed by analysing large quantities of annual maximum rainfall data and superseded the results presented in the FSR (NERC, 1975, Vol. II) 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 is introducing a more comprehensive seasonal analysis than currently available in the existing FSR/FEH method and, therefore, it requires availability of estimates of seasonal design rainfall. As the current project did not allow for a complete frequency analysis and development of seasonal DDF models, as presented by Faulkner (1999) based on annual maximum data, a more pragmatic approach was adopted. 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, where 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

$$R = RDDF*ARF*SCF \tag{5.1}$$

where RDDF is the point estimate of design rainfall obtained from the FEH DDF model, ARF is the areal reduction factor transforming point rainfall to catchment average rainfall and SCR is the seasonal correction factor transforming annual maximum rainfall to seasonal maximum rainfall.

In the following section, a short review of the FEH DDF model will be presented as well as work undertaken as part of the revitalisation project to develop spatially generalised seasonal correction factors (winter/summer) to be applied in the design package.

5.2.1 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

$$\ln[R] = \ln[R_{12}] + (cy + d_2)(\ln[D] - \ln[12]) \tag{5.2}$$

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 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.

5.2.2 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 obtain an estimate of catchment average design rainfall, the concept of the areal reduction factors ARF has been adopted from the existing FSR/FEH method. An ARF is defined by NERC (1975) and Faulkner (1999) 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”. In FEH, the ARF were adopted from Keers and Wescott (1977) and expressed mathematically as

$$ARF = 1 - bD^{-a} \qquad (5.3)$$

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 5.1.

Table 5.1 Areal reduction factor parameters (Keers and Wescott, 1977)

Area A (km^2)	a	B
$A \leq 20$	$0.40 - 0.0208\ \ln[4.6 - \ln[A]]$	$0.0394\ A^{0.354}$
$20 < A < 100$	$0.40 - 0.00382\ (4.6 - \ln[A])^2$	$0.0394\ A^{0.354}$
$100 \leq A < 500$	$0.40 - 0.00382\ (4.6 - \ln[A])^2$	$0.0627\ A^{0.254}$
$500 \leq A < 1000$	$0.40 - 0.0208\ \ln[\ln[A]-4.6]$	$0.0627\ A^{0.254}$
$1000 \leq A$	$0.40 - 0.0208\ \ln[\ln[A]-4.6]$	$0.1050\ A^{0.180}$

In a subsequent review, IH (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, IH (1977) 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 asserted by using relatively short data records and other simplifying assumptions. Despite suggestions in IH (1977) that estimates of *ARF* should be revisited once longer rainfall records were made available no such work has been undertaken to date.

5.2.3 Seasonal correction factors

The ReFH method has adopted the FEH DDF model as the basis for deriving design storms, including the definitions of ARF and storm profiles.

The added emphasis on summer and winter design inputs made necessary the need for specifying seasonal design rainfall input. A reworking of the FEH DDF model considering seasonal maximum, rather than annual maximum rainfall, would be a lengthy task and outside the scope of this study. As an alternative a seasonal correction factor was developed converting the FEH DDF estimate of design rainfall based on annual maximum rainfall into an estimate of seasonal design rainfall through simple multiplication as

$$P_{d,i} = \lambda_{d,i} P_{d,A} \;, \quad \text{i = summer, winter} \qquad (5.4)$$

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 is a correction factor depending on location, season, duration and considered return period. Estimates of $P_{d,i}$ and $P_{d,A}$ (and thereby λ_d) were obtained for a range of return periods by fitting a GEV distribution to series of annual and seasonal maximum rainfall obtained from 523 daily raingauges and 172 subdaily recording raingauges located throughout the UK.

The estimates of the seasonal correction factors showed not to depend strongly on the considered return period and it was considered appropriate to use the values obtained for a return period of T=5 years, enabling a direct comparison with the corresponding seasonal correction factors published in Table 3.9 in the FSR (II.3.5). The seasonal correction factors developed in this study correspond well to the values published in the FSR report. A detailed description of data material and analysis used for development of generic expressions of the summer and winter seasonal correction factors are given in Appendix G and only a summary given here.

Functional relationships between the seasonal correction factors obtained from the observed rainfall series and the *SAAR* catchment description were developed for durations of 1h, 2h, 6h and 1day 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

$$\lambda_d = \begin{cases} \alpha\, SAAR + \beta & \text{summer} \\ \left(1 - \exp\left[\varphi\, SAAR\right]\right)^{\psi} & \text{winter} \end{cases} \qquad (5.5)$$

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. $1 = \alpha 500mm + \beta$. The parameter estimates of the prediction models in Eq. (5.5) are shown in Table 5.2.

Table 5.2 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

To obtain seasonal correction factors for durations other than found in Table 5.2, interpolation between the values in Table 5.2 is recommended. Seasonal correction factors for durations of more than 1day are probably rare in practice but current recommendations are to use the 1day values in such circumstances.

5.3 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 symmetrical 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 (IH, 1979). The two rainfall profiles are shown in Figure 5.1 and the cumulative profiles shown in Figure 5.2. The 50% profle is more peaked than the 75% winter profile, because of the prevalence of intense convective storms in the summer. Faulkner (1999) re-iterated 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).

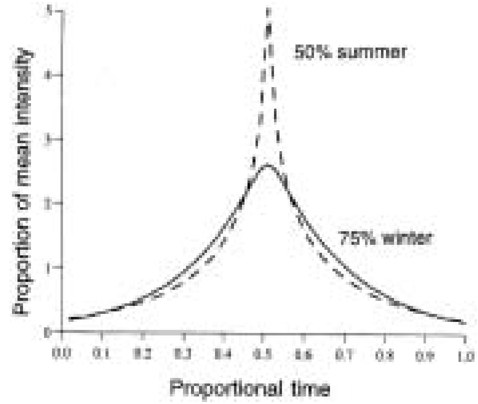


Figure 5.1 Design rainfall profiles for summer and winter drawn as normalised hyetographs

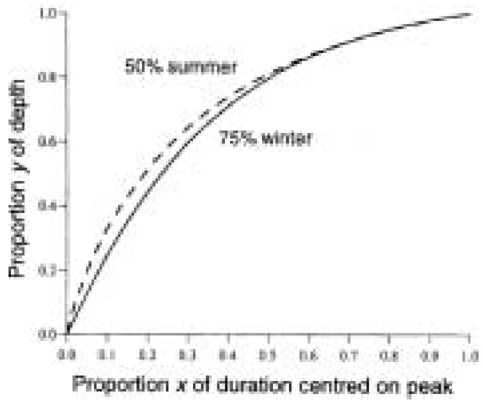


Figure 5.2 Design rainfall profiles, drawn as cumulative proportions of depth and centered on peak.

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

$$y = \frac{1-a^z}{1-a} \qquad (5.6)$$

where $z = xb$ and a and b are profile specific constants listed in Table 5.3.

Table 5.3 Parameters for derivation of design profiles

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

Note, the formula in Eq. (5.6) gives unrealistically large values for the 50% summer profile

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.

5.4 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 (standard average annual rainfall *SAAR*) as

$$D = Tp\left(1 + \frac{SAAR}{1000}\right) \tag{5.7}$$

For the FSR/FEH method it was found that curves of flood magnitude against storm duration are generally flat, indicating that the method is not critically 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. Inclusion of this aspect into the design procedure remains an aspect of the design event method not well researched despite being one of the main arguments for choosing the rainfall-runoff method over the statistical approach to flood frequency analysis.

It is important to chose the design storm duration to be an odd integer multiple of the chosen data interval to enable the design storm hyetograph to be derived correctly. Please refer to Houghton-Carr (1999) Section 3.2.3 for a detailed review of the procedure for generating the design rainfall hyetograph.

6. Development of a new design procedure

In this chapter, a method for estimating T-year design flood events is developed using the ReFH model calibrated to 100 sites throughout the UK (Chapters 3 and 4) as well as the design rainfall model described in Chapter 5.

6.1 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 used in model calibration in Section 4.1) 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 objective of the project is the development of an improved rainfall-runoff method that could 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 uniquely 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. In the current study, the 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.

6.2 The FSR/FEH design model

The FSR/FEH design method is described in detail by Houghton-Carr (1999). The method requires the profile and the duration of the design rainfall and the antecedent soil moisture (CWI) to be estimated based on attributes of the considered catchment. The required return period of the resulting design hydrograph is ensured by specifying the return period of the required rainfall. The FSR/FEH design method adopted a specific relationship between the return period of the design rainfall and the resulting design hydrograph to ensure that the flood frequency curve of the peak flow of the design hydrograph matched the corresponding flood frequency curve of the observed annual maximum peak flow at each considered site. The method was calibrated on 98 catchments by considering flood of a return period of 2 and 10 years, i.e. far from the 100-year return period for which the method is routinely used at present.

The FSR report (I.6.7.3-6) investigated the sensitivity of each of the four flood generating mechanisms listed above (rainfall depth, duration, profile and antecedent soil moisture) and 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 antecedent soil moisture. Considering rainfall depth and antecedent soil moisture, it was found that a relationship between the return periods of the generating design storms and the resulting design floods could be identified, which varied little between catchments. However, when using the antecedent soil moisture variable CWI as the free variable to match rainfall and peak flow frequency curves, it was found to vary between catchments, which was considered untenable.

6.3 The ReFH design model – basic assumptions

The design model developed in this study is based on the ReFH model as illustrated in Figure 6.1

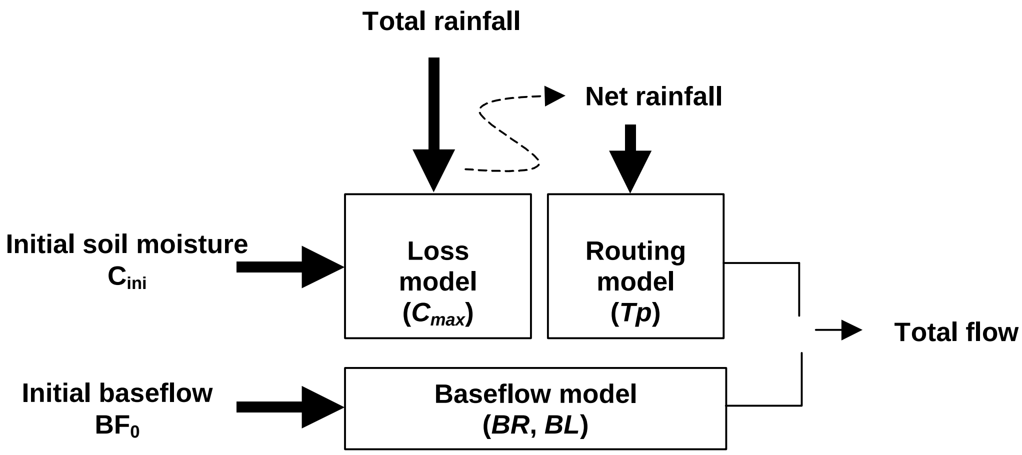


Figure 6.1 Schematic of the ReFH design model

The design model consists of the same model elements as the ReFH model described in Section 3, but requires design values of rainfall, initial soil moisture and initial baseflow rather than observed values.

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 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. 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.

6.4 Calibration procedure

The existing FSR/FEH method has been widely criticised for over estimating design floods when compared to the corresponding estimates obtained through a statistical analysis of AMAX events. Consequently, the ReFH design method is calibrated to ensure that the flood frequency curves derived from the method correspond to the flood frequency curves derived through a statistical analysis of AMAX events.

When estimating a *T*-year flood using the FEH statistical method it is recommended that, unless a record of AMAX peak flow of a minimum length of two times the required return period is available at the site of interest, pooled analysis should be applied. Considering return periods of up to 100 years, as in this study, implies that pooled analysis should be applied on all catchments. To ensure consistency in the development of the design model it was decided to use pooled analysis on all catchments and for estimating *T*-year events for all considered return periods.

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 6.2) is minimised by adjusting the free variable, i.e.

$$\min_{\theta}\left\{\left(\frac{Q_{T,ReFH}(\theta)-Q_{T,Stat}}{Q_{T,Stat}}\right)^2\right\}=\min_{\theta}\left\{d_T^2(\theta)\right\} \qquad (6.1)$$

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).

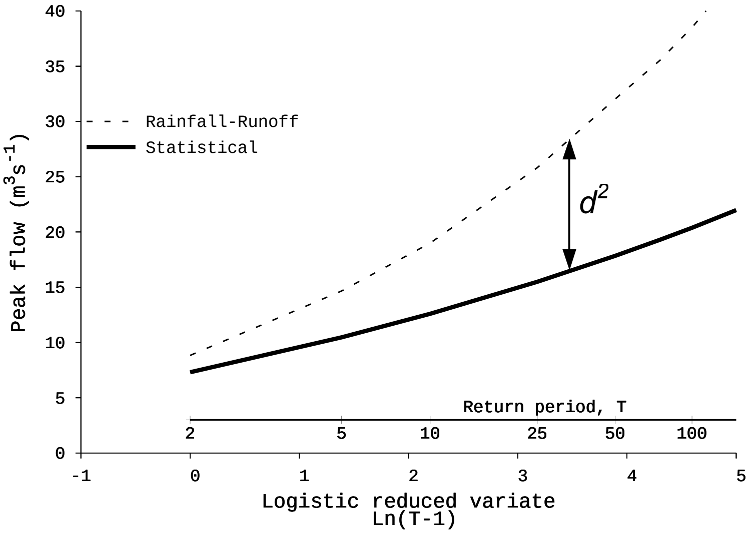


Figure 6.2 Difference between flood frequency curves from pooled statistical method and as generated by the ReFH model. Calibration performed by minimising d^2 for each return period.

Initial attempts to reconcile the FEH design rainfall with the pooled flood estimates through the ReFH model proved problematic as the FEH rainfall growth curves are generally steeper than the corresponding pooled flood frequency curves as illustrated in Figure 6.3, where the ratio between the 5-year and 100-year growth factors (i.e. the steepness of the growth curve) are compared for the FEH rainfall (derived for the critical duration of each individual catchment) and the pooled flood frequency curves for a subset of the 101 catchments.

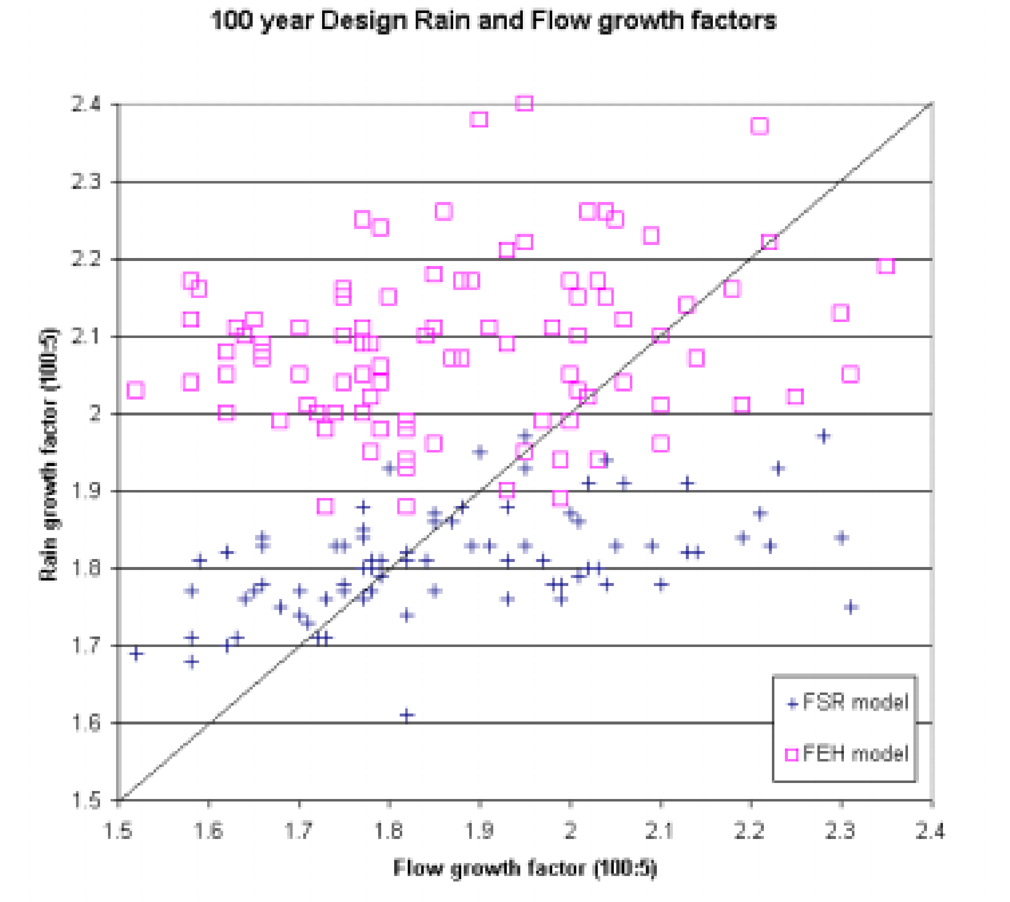


Figure 6.3 Comparison of steepness of growth curves for FEH and FSR design rainfall and pooled statistical flood frequency analysis.

The steeper rainfall growth curves require the flood peak magnitude output from the ReFH design model to increase at a slower rate in order to align the observed and modelled output flood frequency curves. 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.

The first option for reconciling the two methods was chosen in the development of the FSR method and has subsequently led to much confusion concerning how to interpret the resulting relationship, i.e. why does the T=140 year rainfall event result in a 100 year flood? It was decided not to follow this route in this project in order to increase transparency. The second option, to introduce increasingly dry initial conditions at higher return periods, is clearly counter intuitive, especially for winter flooding. Furthermore, the initial baseflow value depends on the initial soil moisture (see Eq. (7.11) and Eq. (7.12)) 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 in Section 4. Furthermore, few large events are available for justifying any changes at high return periods. In Section 4.6, the effect of event magnitude on the time to peak (Tp) parameter was investigated. No quantifiable trend was identified though evidence seems to suggest a reduction in *Tp* for very large events could be warranted. 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 Section 3 and in Eq. (3.3) 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 Eq. (6.2) below

$$\frac{Q}{P} = \begin{cases} \alpha_T \left(C_{ini} / C_{\max} \right) + \left(P / 2C_{\max} \right) & t = 1 \\ \left(C_{t-1} / C_{\max} \right) + \left(P / 2C_{\max} \right) & t = 2,3,... \end{cases} \tag{6.2}$$

and $C_t = C_{t-1} + P_t$

Note the difference between the design model loss model (equation 7.2) and the loss model used when analysing the observed events (equation 3.3). The factor α_T is used in the calibration procedure as the free variable. The coefficient does not have a direct physical interpretation and will only be used when estimating a design hydrograph.

6.5 Seasonality

To allow 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 prone to summer or winter flooding.

The FSR/FEH method does not explicitly consider flooding in different seasons and the only design input variables with distinct seasonal variation is the design rainfall profile and the rainfall/runoff return period scaling factor. If a catchment is considered rural (*URBEXT* < 0.125) then a winter design profile is used but if the catchment is heavily urbanised (*URBEXT* ≥ 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 (IH, 1979) to ensure compatibility with design methods used in urban drainage.

The problem of how to characterise the seasonal flooding pattern of a catchment without access to hydrological data is essential, as the design method is anticipated to be used mainly at ungauged sites. Unfortunately, limited research efforts have been concentrated on addressing this issue, 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 located 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 for the purpose of this study, the definition used in the FSR/FEH method to distinguish between rural and urban catchments was adopted in this study to separate the available catchments into summer (*URBEXT* ≥ 0.125) and winter catchment (*URBEXT* < 0.125), respectively. Based on this definition the 100 catchments give 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.

6.6 Pooled frequency analysis

The procedure for conducting pooled flood frequency analysis as outlined by Robson and Reed (1999) is time consuming and, preferably, requires expert knowledge of the site of interest. In this study estimates are required at 100 different catchments and, 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 considered 100 catchments. The pooling group was created for a target return period of *T*=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 located 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 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 on terms of *AREA, SAAR* and *BFIHOST*. Although the FEH showed the pooling method to perform better than the FSR regions, in general, it should be recognised that 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 either: 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 on sites with these characteristics when comparing to single site analysis.

6.7 Initial soil moisture content

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 T=5 year return period (α_5 = 1), the corresponding values of C_{ini} can be derived using the calibration procedure outlined above, i.e. aligning the derived T=5 year estimates with the statistical estimate of the T=5 year 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.

In Figure 6.4 the observed values of $C_{ini}/0.5C_{max}$ for each of the 1259 observed flood events analysed in Section 4 are plotted together with the corresponding design values for each of the 100 analysed catchments. The catchment number along the x-axis corresponds to the order of the catchments as listed in Appendix F, i.e. catchment number 1 in Figure 6.4 is 7001 Findhorn at Shenachie.

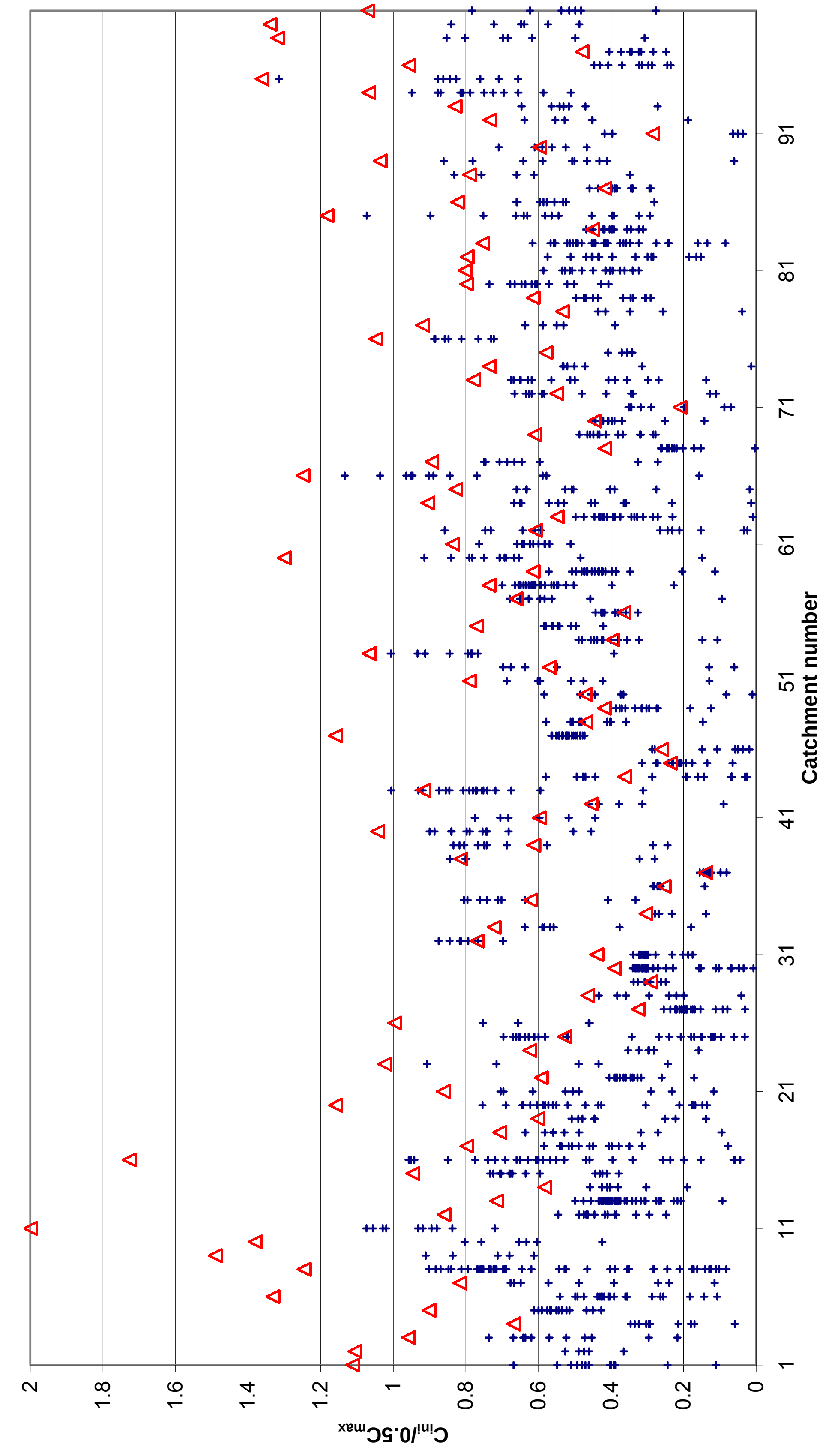


Figure 6.4 **Observed and design values of $C_{ini}/0.5C_{max}$ for each of the 101 analysed catchments.**

From Figure 6.4 it is apparent that, in general, the order of magnitude of the design values of C_{ini} corresponds to the observed values. In Figure 6.5 the design $C_{ini}/0.5C_{max}$ is plotted against the maximum observed $C_{ini}/0.5C_{max}$ value for each catchment.

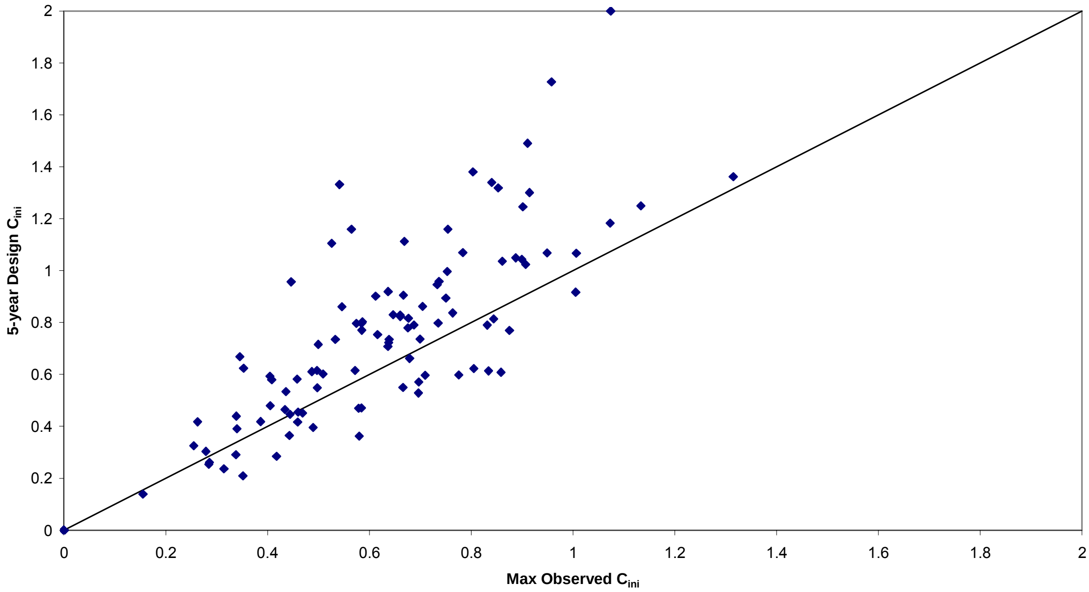


Figure 6.5 Design C_{ini} plotted against maximum observed values for each catchment.

The plot in Figure 6.5 shows that the design values of C_{ini} compare favourably to the maximum observed values of C_{ini} on most catchments, with a tendency of the design values to slightly exceed the observed values. This is a reassuring result as the design values will be used for estimation of design floods with return periods in excess of the observed events available on most catchments. The plots in Figure 6.4 and Figure 6.5 confirm that the derived design values of C_{ini} are comparable to the values obtained from analysing the observed events with a tendency of approaching or exceeding the largest events. This was found to be reasonable considering the use of the design values for the generation of design floods.

In the FSR/FEH method the catchment wetness index (CWI) was linked to the catchment average standard annual average rainfall (*SAAR*) derived for the period 1961-1990 through a graphical representation, but no mathematical linking of the two variables was provided. In this study, the ratio between C_{ini} and $0.5C_{max}$ has been linked to a set of catchment descriptors through multivariate linear regression and a comprehensive search procedure used to identify the optimal combination, as outlined in Chapter 7. The optimal description, considering both the number of variables and increase in predictive power when adding extra variables, was found to be achieved by describing the $C_{ini}/0.5C_{max}$ ratio using *PROPWET* and *BFIHOST* as

$$
\begin{aligned}
&C_{ini,winter}/0.5C_{\max} = 1.20 - 1.70\ BFIHOST + 0.82\ PROPWET\\
&n = 93, \quad r^2 = 0.53\\
&C_{ini,summer}/0.5C_{\max} = 0.90 - 0.82\ BFIHOST - 0.43\ PROPWET\\
&n = 7, \quad r^2 = 0.49
\end{aligned}
\tag{6.3}
$$

The relationships developed in Eq. (6.3) ensure that the initial soil moisture content increases with increasing wetness of the soil (*PROPWET*) and decreases for permeable catchments with increasing *BFIHOST*. In the rare case where the $C_{ini}/0.5C_{max}$ ratio calculated in Eq. (6.3) falls below zero, the ratio is set to zero.

The introduction of a soil related catchment descriptor in the equation predicting initial soil conditions is considered an improvement over the existing method where only annual average rainfall was considered. From Eq. (6.3) absolute values of C_{ini} can be obtained by multiplying the ratios with mean soil depth $0.5C_{max}$.

6.8 Results

Having specified the design values of the initial conditions, C_{ini}, the ReFH design method can be calibrated by adjusting the α-T coefficient for the winter and summer catchments, respectively, as outlined in Section 6.7. The outcome of the calibration procedure is an α_T coefficient for each catchment and for each considered return period. The final design values of α_T will be derived by considering the summer and winter catchments separately. For each season, α_T are derived as a simple average over all the catchments for each return period. The resulting design values of α_T for both the winter and summer catchments are shown in Figure 6.6.

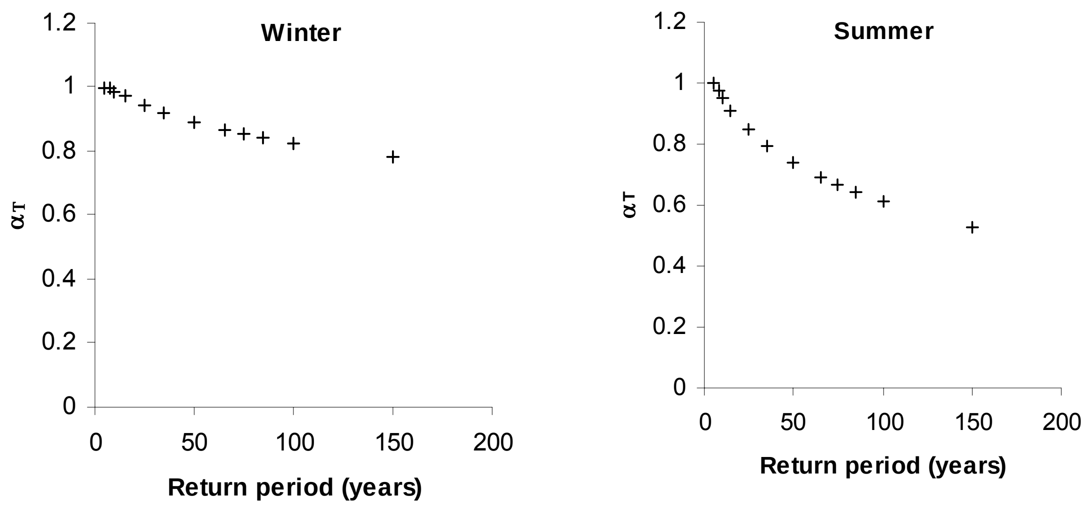


Figure 6.6 The α_T-coefficient for summer and winter, respectively

From Figure 6.6 It is clear, that a more significant adjustment is needed on summer catchments than on winter catchments. A number of reasons for the observed differences in α_T between the two seasons can be listed. It might be due to sampling uncertainty bearing in mind that data from only seven gauging stations have been used for calibration of the summer season design model. Another possibility is that the statistical pooling method produces growth curves that are too flat in urban catchments, which will require a larger reduction of (smaller α_T values) in the ReFH in order to align the growth curves from the two methods. More research is required before the exact reasons can be known.

To use the design model, the user is required first to set up the ReFH model, i.e. estimating the four ReFH parameters (C_{max}, *Tp, BL* and *BR*) either through analysis of observed events or using predictor equations based on the catchment descriptors developed in Chapter 7. Next, the design values of rainfall (depth, duration and profile) and initial soil moisture content (C_{ini}) need to be specified in order to generate the T-year flood. As the values of αT depend only on the required return period, the value does not vary from catchment to catchment.

7. Catchment descriptor equations

To enable the ReFH rainfall-runoff to be applied to any UK catchments larger than 0.5 km^2, relationships between the four model parameters (*BL*, *BR*, C_{max} and *Tp*) and catchment descriptors need to be established. In this study the ReFH model parameters estimated at 101 gauged sites in Section 4 are linked to catchment descriptors readily available on the FEH CD-ROM (Bayliss, 1999) through the use of multivariate linear regression.

7.1 Introduction

The FSR/FEH model adopted multiple linear regression for the development of predictor equations relating model parameters to catchment characteristics and catchment descriptors as reported by NERC (1975), IH (1985), Marshall and Bayliss (1994), Houghton-Carr (1999) and Marshall (2000).

In the most recent investigation using the digital catchment descriptors, Marshall (2000) found the time to peak (*Tp*) parameter could best be predicted using information concerning catchment slope (*DPSBAR*), catchment wetness (*PROPWET*), drainage path length (*DPLBAR*) and degree of urbanisation within the catchment (*URBEXT*). This combination corresponded well to the findings of some of the pre-FEH investigations (NERC, 1975; Boorman 1985), where information concerning average rainfall was used rather than catchment wetness, as the latter was not easily available at the time.

In the FSR/FEH model, the estimation of rainfall losses at ungauged sites is related to catchment descriptors of soil type (*SPRHOST*) and degree of urbanisation (*URBEXT*). However, the anatomy of the loss model in ReFH is fundamentally different from the FSR/FEH model, hence, these results are not of direct use and should not restrict the search for good predictors in this study.

The following section contains a description of the dataset used in the analysis and the results obtained from the statistical analysis.

7.2 Data Material

The data material required for this analysis encompasses a set of dependent data (model parameters) and the corresponding independent descriptors (catchment descriptors).

7.2.1 Model parameters

From applying the ReFH model to each of the 101 gauged catchments and 1265 events, coherent sets of the four ReFH parameters were estimated as described in Section 4. The full list of catchments and their optimised parameter values are shown in Appendix F.

7.2.2 Catchment descriptors

Eight catchment descriptors readily available from the FEH CD-ROM (Bayliss, 1999) were used in this study covering aspects of topography, soil, rainfall, urbanisation and lakes and reservoirs. A summary of each catchment descriptor is given in Table 5.1, and a more detailed description is provided in Volume 5 of the FEH. *SPRHOST* was included in initial exploratory investigations but later omitted in favour of providing models based upon *BFIHOST*, which is a more robust descriptor than *SPRHOST* as it is based on a significantly larger data set. A dummy catchment descriptor of randomly generated numbers was also included in the regression analysis. The presence of the random variable in the final model would indicate that the model contains too many explanatory variables and that no further information catchment descriptors can beneficially be added to the model.

Table 7.1 Catchment descriptors used to develop predictor equations

Descriptor	Unit	Range	Note
AREA	km^2	[0; ∞]	Catchment area defined by IHDTM boundary
SAAR	mm	[0; ∞]	Standard-period average annual rainfall (1961-1990)
BFIHOST	-	[0; 1]	Base flow index from the Hydrology of Soil Types classification.
FARL	-	[0; 1]	Index of flood attenuation due to reservoirs and lakes.
PROPWET	-	[0; 1]	Proportion of time catchment soils are wet during 1961 – 1990
DPLBAR	[km]	[0; ∞]	Mean drainage path length defined by IHDTM.
DPSBAR	[m/km]	[0; ∞]	Mean drainage path slope defined by IHDTM.
URBEXT	-	[0; 1]	Extent of urban and suburban land cover (1990)

When developing the predictor equations through linear regressions, it is important to ensure that catchment descriptors used in the analysis can be considered independent. A correlation matrix showing the correlation coefficient between pairs of catchment descriptors is shown in Table 7.2

Table 7.2 Matrix of correlation coefficients between catchment Descriptors

	AREA	*SAAR*	*BFI-HOST*	*FARL*	*PROP-WET*	*DPLBAR*	*DPSBAR*	*URBEXT*
AREA	1.00							
SAAR	0.14	1.00						
BFIHOST	0.01	-0.19	1.00					
FARL	-0.17	0.09	0.01	1.00				
PROP-WET	0.20	**0.78**	-0.30	0.08	1.00			
DPLBAR	**0.89**	0.08	-0.02	-0.17	0.14	1.00		
DPSBAR	0.23	**0.82**	-0.15	0.10	**0.73**	0.20	1.00	
URBEXT	-0.25	-0.22	-0.01	-0.04	-0.29	-0.26	-0.26	1.00

Numbers in **bold** indicate a correlation coefficient larger than 0.7.

From Table 7.2 it is evident that some of the catchment descriptors are highly correlated, and inclusion of both in a predictor equation should be avoided. For other combinations, the correlation arises as one descriptor appears to be a surrogate variable for another, for example, catchments with large average slope (*DPSBAR*) tend to be located in more hilly areas, which again are located at high altitudes where the annual rainfall (*SAAR*) tend to be large. The data comprises catchment areas ranging from 3.4 and 511 km^2. A complete list of catchment descriptor values for each catchment is shown in Appendix E.

7.3 Multivariate linear regression

7.3.1 Model formulation

Relationships between model parameters and catchment descriptors were developed based on least square multiple linear regression techniques. Consider the assumed log-linear relationship between a model parameter y_i and a set of *p* different catchment descriptors given as

$$\ln[y_i] = \ln[b_0] + \sum_{k=1}^{P} b_k \ln[x_{k,i}] + \varepsilon_i \qquad (7.1)$$

where

y_i = ReFH model parameter at the *i*'th site, i=1,…N,

b_k = regression model parameter, j= 0, …, P,

$x_{k,i}$ = catchment descriptor k = 1, …, p at the *i*'th site, and

ε_i = NID model error due to lack of fit of regression model at the *i*'th site.

Use of the natural logarithm in Eq. (7.1) on an independent variable, which can take zero as a value is not possible, thus *URBEXT* is replaced by 1+*URBEXT*.

The simplest approach for estimating the regression model parameters is ordinary least square (OLS), where all observations are treated as being independent and having residual errors of equal variance. The first assumption concerning independence is considered valid in this application, as it is considered unlikely that the available flood events at different sites are overlapping significantly in time. The second assumption, however, concerning equal variance is clearly flawed as the model parameters have been derived at different catchments using a varying number of flood events. Therefore, instead of OLS, the regression model parameters are estimated using weighted least square (WLS), which is similar to 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.

$$w_i = \sqrt{n_i} \tag{7.2}$$

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.

Model performance

Two types of performance criteria were adopted to identify the optimal combinations of catchment descriptors for predicting ReFH parameters at ungauged sites. First, a statistical criterion based on a leave-one-out approach was defined to give a numerical basis for comparing the performance of different prediction models. Secondly, hydrological criteria will ensure that the final models are underpinned by sound hydrological judgement.

A statistical criterion

The choice of catchment descriptors on which to base the predictor equations is difficult. A number of statistical criteria for assessing the goodness of fit of a particular model exist. In this study, the predicted error sum of square (PRESS), the coefficient of determination, (r^2) and the factorial standard error (*fse*). The PRESS statistic is based on a leave-one-out cross validation approach. Each site is removed from the analysis in turn and its value predicted using the remaining sites (Robson and Reed, 1999), and the PRESS statistic is calculated as

$$PRESS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left\{y_i - \hat{y}_{(i)}\right\}^2} \tag{7.3}$$

where
N = number of catchments,
y_i = observed ReFH model parameter for the ith catchment, and
$\hat{y}_{(i)}$ = estimate of ReFH parameter for the omitted ith catchment.

An estimate of the *PRESS* statistic is obtained for each model parameter and for each possible combination of catchment descriptors. Lower values of *PRESS* indicate a better model performance. Note that the *PRESS* statistic depends on the magnitude of the parameter under consideration, i.e. it cannot be used to compare goodness of fit between parameters.

The coefficient of determination is a widely used measure of performance for linear regression models, measuring the proportion of variance explained by the proposed model. Note, however, that r^2 always increases as further variables are added to the model. The point at which the increase of r^2 starts to slow down may indicate a suitably descriptive model.

The factorial standard error (*fse*) is also used as an indicator of the model uncertainty. It is estimated from the error of the fitted model i.e. the root mean square error of the fitted model measured on the log scale.

Hydrological criteria

Hydrological judgement should be used to determine whether different models are physically plausible. Special consideration should be given to the fact that the ReFH model is a physically based rainfall-runoff model applicable to a wide range of catchments. Therefore, the catchment descriptors used to predict the individual ReFH model parameters should be linked to the major physical processes described by the ReFH model parameter.

7.4 Results

To identify the optimal sets of catchment descriptors to be used in Eq. (5.1), an automated procedure was developed where regression models are estimated for all possible subsets containing p = 1, …, 9 of the nine catchment descriptors listed in Table 7.1. For each regression model the *PRESS* statistic, the coefficient of determination (r^2) and the factorial standard error (*fse*) were calculated. Unless specified otherwise, both the ReFH model parameters and the catchment descriptors were transformed using the natural logarithm before the regression models were estimated.

7.4.1 Time to peak (Tp)

The estimated time to peak parameter values for the 101 catchments are in the range 0.5 – 24.2 hours. Both the FSR and FEH studies found that a reasonable regression model linking *Tp* to catchment characteristics or descriptors describing catchment slope, degree of urbanisation, catchment wetness and drainage path length could be estimated.

The estimated regression models, based on two, three, and four catchment descriptors, with highest r^2 and *fse* are shown in Table 7.3.

Table 7.3 Regressions for time to peak, ln[*Tp*], for equations containing two, three and four catchment descriptors.

	r^2	Adj.r^2	*fse*	PRESS	Variable	Coeff.	Standard error of coefficient	t-statistic
2	0.67	0.67	1.45	7.43	Constant *PROPWET* *DPLBAR*	-1.338 -1.337 0.703	0.216 0.125 0.065	-6.200 -10.679 10.793
3	0.76	0.75	1.36	8.22	Constant *PROPWET* *DPLBAR* *1+URBEXT*	-1.097 -1.540 0.586 -3.083	0.190 0.113 0.059 0.518	-5775 -13.635 9.891 -5.956
4	0.81	0.80	1.32	8.23	Constant *PROPWET* *DPLBAR* *DPSBAR* *1+URBEXT*	0.447 -1.086 0.598 -0.278 -3.340	0.368 0.140 0.054 0.059 0.472	1.213 -7.747 11.131 -4.740 -7.084

N = 101

The best performing five parameter equation included *FARL*. However, adding *FARL* as the fifth descriptor showed insignificant improvement to the fit of the model and its addition was only marginally better (a difference in r^2 of 0.0001) than including the random component. Whilst it maybe expected that *FARL* should be more prominent in these equations it must be highlighted that the dataset contained just one catchment with a significantly low *FARL*. The majority of catchments (99%) had a *FARL* in the range 0.9 - 1.0.

The four parameter equation in Eq. (7.4) is selected as providing maximum explanation of *Tp*.

$$Tp = 1.563 PROPWET^{-1.09} DPLBAR^{0.60} (1+URBEXT)^{-3.34} DPSBAR^{-0.28} \qquad (7.4)$$

r^2 = 0.81; fse = 1.32, *N*=101

Observed values of *Tp* are plotted against predicted values from Eq. (7.4) in Figure 7.1 and a generally good correspondence between the two values is observed.

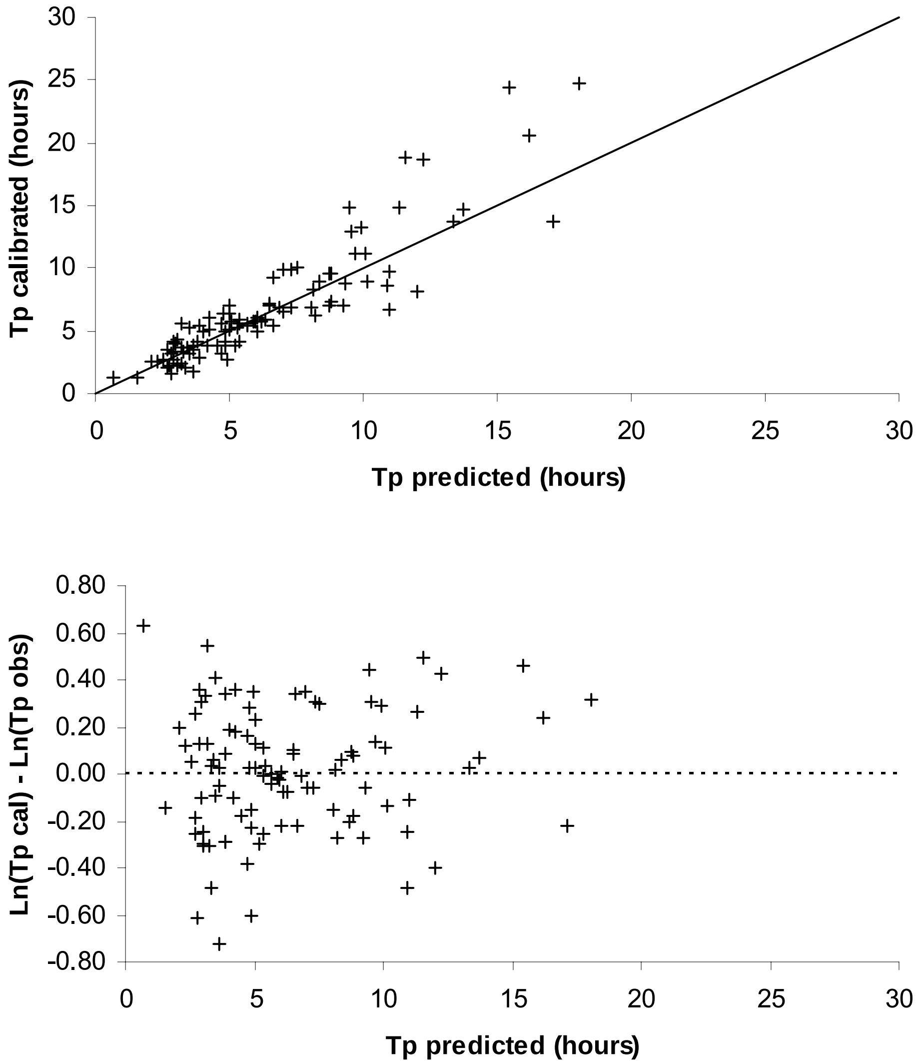


Figure 7.1 Plot of *Tp* observed vs predicted and ln(*Tp* predicted) against residuals using Eq. (7.4).

The new ReFH four-parameter model for *Tp* is very similar to that produced by Marshall (2000) and reported in FEH by Houghton-Carr (1999), using the same digitally derived catchment descriptors.

The equation developed for the ReFH model in this study provides improved prediction of *Tp* when compared to the FEH with a decrease in the factorial standard error of 0.09 from 1.85 (FEH) to 1.76 (ReFH).

Notably, in the FEH the exponents of catchment slope (*DPSBAR*) are very similar; the exponents, *PROPWET* and *DPLBAR*, increase in magnitude and the *URBEXT* exponent is slightly reduced. The positive exponent for mean drainage path length means that the time to peak increases as the distance flood waters travel increases, likewise the negative exponents on *DPSBAR*, *PROPWET* and *URBEXT* indicate a decreasing time to peak on increasingly steep, wet and urban conditions.

Times to peak beyond 15 hours tend to be underestimated. A separate regression model for catchments with Tp estimates of less than 15 hours was considered. However, no significant improvement was observed and the introduction of an arbitrary threshold of 15 hours was considered an unnecessary complication of the method for practical use.

7.4.2 Loss model parameter (C_{max})

The loss model parameter C_{max} is derived from the two model parameters *SM* and *FC* according to:

$$C_{max} = 2 \times FC \times SM \tag{7.5}$$

As explained in Section 3.2.4, the field capacity (*FC*) was fixed in the model whilst the coefficient *SM* remained an important free variable in the parameter optimisation procedure. Of the regression models tested in log space, *BFIHOST* and *PROPWET* emerged as the most significant descriptors. One catchment, (34003) was found to be a significant outlier, resulting from the unusually high value of C_{max} (C_{max} = 1363 mm with the second highest value being C_{max} = 770 mm). This catchment, the Bure at Ingworth, is located in Norfolk, a sandy catchment characterised by a high baseflow index with *BFIHOST* = 0.77, the highest in this dataset. Removing this point does, however, reduce the range of *BFIHOST* available in the dataset from 0.18 to 0.66.

Table 7.4 Regressions on C_{max} for one, two and three catchment descriptors

	r^2	Adj.r^2	fse	PRESS	Variable	Coeff.	Standard error of coefficient	t-statistic
1	0.52	0.52	1.63	106.31	Constant *BFIHOST*	6.670 1.026	0.088 0.099	75.574 10.270
2	0.55	0.54	1.61	586.99	Constant *BFIHOST* *PROPWET*	6.379 0.947 -0.243	0.135 0.101 0.091	47.366 9.415 -2.670
3	0.55	0.54	1.61	496.55	Constant *BFIHOST* *PROPWET* *1+URBEXT*	6.383 0.945 -0.257 -0.182	0.137 0.101 0.097 0.401	46.631 9.326 -2.662 -0.4542

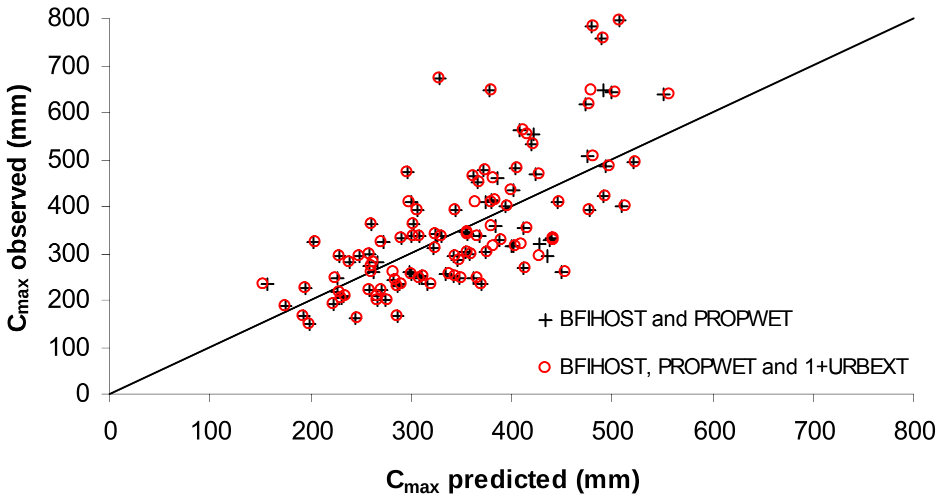
n = 100, excl. 34003

From Table 7.4 it can be observed that the two parameter equation provides reasonable explanation of the parameter C_{max} and was therefore adopted, i.e.

$$C_{\max} = 596.7 BFIHOST^{0.95} PROPWET^{-0.24} \tag{7.6}$$

r^2 = 0.55, fse = 1.61, *N*=100

Hydrological judgement would point to the inclusion of the *URBEXT* term in the equation and this is supported by past experience (NERC, 1975; Packman, 1980 and Boorman, 1985), in which the extent of urbanisation has been included in the equations predicting Percentage Runoff. However, on consideration of the above regressions, the t-statistic for the *URBEXT* term (Table 7.4) does not support its inclusion in the final equation and it is shown graphically in Figure 7.2 that this descriptor makes only small adjustments to the C_{max} value. These models have been derived from catchments of *URBEXT* ranging from 0.000 to 0.433 of which 10% exceed URBEXT value of 0.1, hence, the minimal influence of the *URBEXT* term is not due to insufficient representation of urban catchments in the dataset. One important difference between the model sought here and those derived for percentage runoff is that the model is not derived from the results of individual events but rather the optimised catchment values. Thus the *URBEXT* signal which may be stronger for particular events is obscured and smoothed during parameter optimisation process.



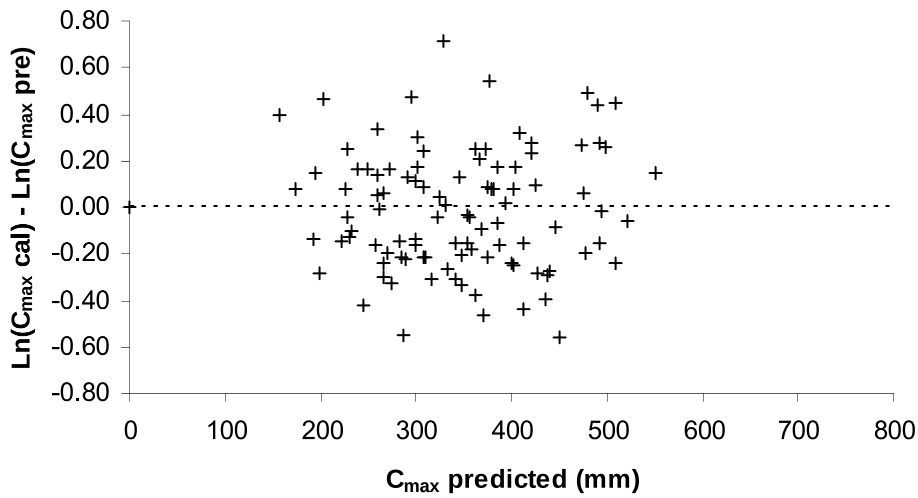


Figure 7.2 Influence of *URBEXT* on predictions of C_{max} and plot of logarithmic residuals against predicted values of C_{max}

The results in Figure 7.2 indicate that the adopted regression model potentially has a tendency to under-estimate values of C_{max} when the observed values exceed 500 mm. This problem might be related to the observations made in Section 4.4.4 that very high values of *SM* (C_{max}) were reported in baseflow dominated catchments. The results here emphasise the need for caution when applying the ReFH model parameters to baseflow dominated catchments.

7.4.3 Baseflow parameters

The increased complexity of the baseflow component in the ReFH model requires definition of the relationships for the parameters baseflow lag (*BL*) and baseflow recharge (*BR*) in addition to estimating initial baseflow (BF_0). The model parameters *BL* and *BR* have, like *Tp* and C_{max} been calibrated across a series of events to yield a catchment optimum and hence are derived using the sample size of 101 catchments. Initial baseflows were captured for each of 1199 events and the derivation of these equations is described in Section 7.4.4.

Baseflow Recharge (*BR*)

Attempts to identify suitable regression models for predicting *BR* found most catchment descriptors to be poor predictors with only *BFIHOST*, *PROPWET* and *DPLBAR* having any significant explanatory power. The catchment 28046, Dove at Izaak Walton was found to be an outlier with a high value of *BR* = 4.05 compared to 3.29 for the 2nd largest value in the dataset.

Table 7.5 Regression results for parameter *BR*

	r^2	Adj.r^2	fse	PRESS	Variable	Coeff.	Standard error of coefficient	t-statistic
2	0.34	0.33	2.04	0.996	Constant *BFIHOST* *PROPWET*	1.322 1.077 0.357	0.207 0.152 0.138	6.386 7.094 2.581
2	0.38	0.36	2.01	0.953	Constant *BFIHOST* *DPLBAR*	0.260 0.913 0.232	0.224 0.141 0.067	1.158 6.460 3.445
3	0.39	0.38	1.99	1.24	Constant *BFIHOST* *PROPWET* *DPLBAR*	0.648 1.005 0.252 0.199	0.307 0.149 0.138 0.069	2.110 6.769 1.827 2.886

n = 100, excl. 28046

From the results in Table 7.5 it can be observed that a model using *BFIHOST* and *DPLBAR* performs slightly better than a *BFIHOST*, *PROPWET* based model. However, there is no hydrological reason why *DPLBAR* should have a significant influence on baseflow recharge, thus, the model containing *DPLBAR* was disregarded. Similarly, the best performing regression model based on three catchment descriptors also contains *DPLBAR* (as well as *BFIHOST* and *PROPWET*). While the model using three catchment descriptors performs marginally better than the corresponding two parameter models in terms of r^2 and *fse*, the *PRESS* statistic has deteriorated and, combined with the use of *DPLBAR*, this led to the dismissal of this model. As a result, the regression model based on *BFIHOST* and *PROPWET* only was adopted for prediction of *BR*, i.e.

$$BR = 3.751\,BFIHOST^{1.08}PROPWET^{0.36} \qquad (7.7)$$

r^2 = 0.34, *fse* = 2.04, *n*=100

The signs of the exponents describe the situation of increased baseflow recharge in catchments with high *BFIHOST* (i.e. permeable catchments) and high *PROPWET* (conditions of increasing catchment wetness) which are in agreement with the dominating physical processes controlling the recharge.

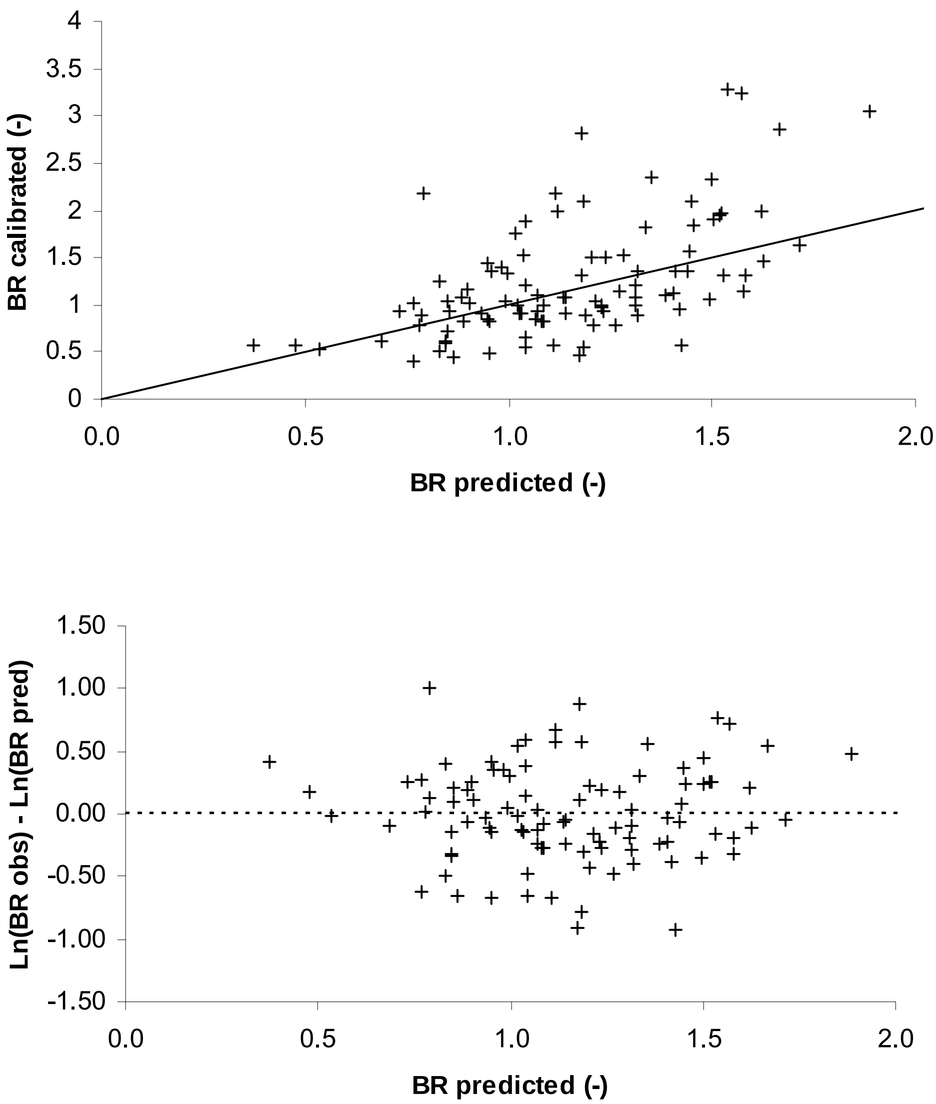


Figure 7.3 Predicted *BR* plotted against observed *BR* including a 1:1 line and logarithmic residuals plotted against predicted values of *BR*

Values of *BR* estimated using Eq. (7.7) are plotted against the corresponding estimates obtained from observed data in Figure 7.3. This figure indicates that the derived regression model tends to slightly overestimate low values of *BR* and underestimate high values of *BR*, respectively.

Baseflow Lag (*BL*)

The regression analysis revealed *BFIHOST, URBEXT, PROPWET* and *DPLBAR* to be the strongest explanatory variables. Again the catchment 28046 was an outlier with *BL* = 146.5, significantly higher than the main body of data. The best performing two and three variable predictor equations contained combinations of these descriptors with the four variable equation (Eq. 7.6) emerging as the best fitting model overall. Coefficients of the four parameter equation are shown in Table 7.6

The predictor equation for the baseflow lag *BL* is:

$$BL = 25.47 BFIHOST^{0.47} DPLBAR^{0.21} PROPWET^{-0.53} (1 + URBEXT)^{-3.01} \qquad (7.8)$$

r^2 = 0.41, *fse* = 2.03, *N* = 100

High *BFIHOST* and long drainage path lengths correspond to a high lag whilst high values of *PROPWET* and high *URBEXT* were found to correspond with low lags.

Table 7.6 Regression results for parameter *BL*

	r^2	Adj.r^2	*fse*	*PRESS*	Variable	Coeff.	Standard error of coefficient	*t*-statistic
4	0.41	0.39	2.03	118.61	Constant	3.238	0.319	10.15
					BFIHOST	0.473	0.153	3.09
					PROPWET	-0.528	0.147	-3.59
					DPLBAR	0.209	0.074	2.82
					1+URBEXT	-3.012	0.626	-4.81

n = 100, excl. 28046

In Figure 7.4 (overleaf) observed estimates of *BL* are plotted against the predicted values derived using Eq. (7.8).

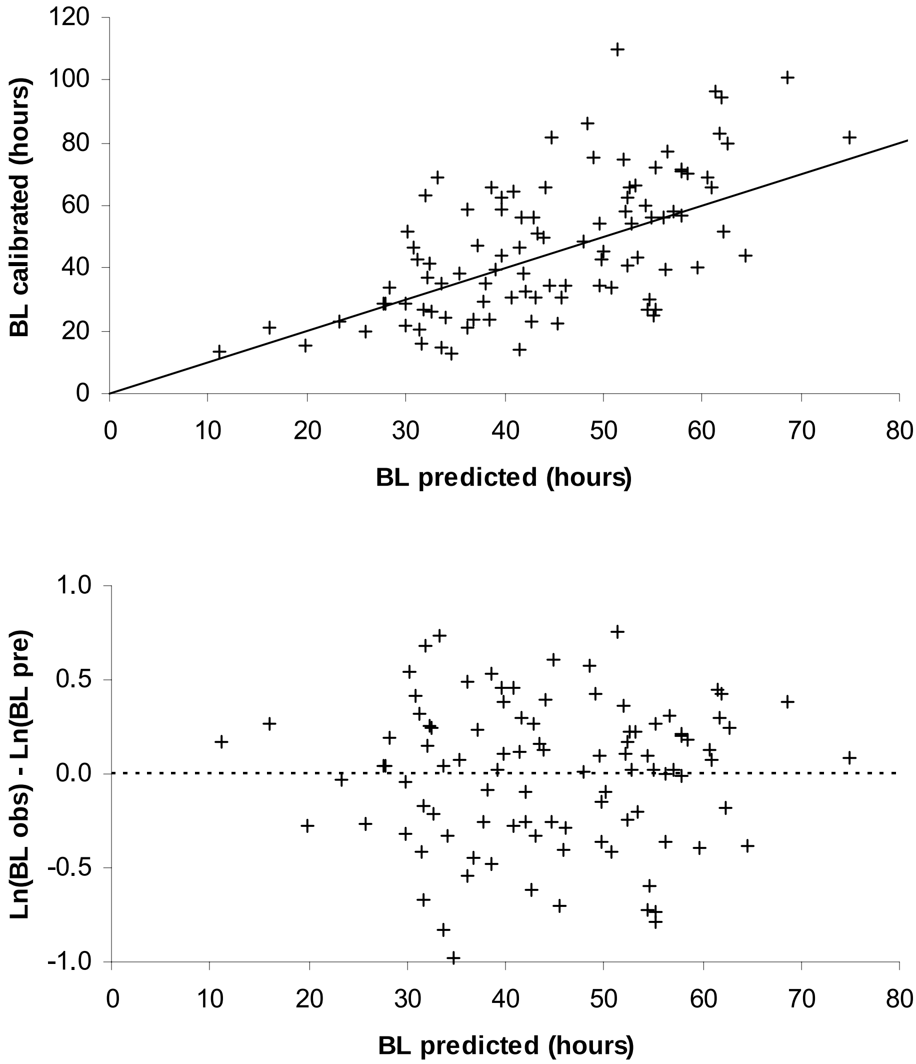


Figure 7.4 Predicted vs. observed values of Baseflow Lag (*BL*) and logarithmic residuals plotted against predicted values of *BL*

As for the baseflow recharge, the regression model tends to underestimate *BL* where low values have been observed and overestimate where large values have been observed, though, the problem is less severe than for *BR*.

However, for both *BR* and *BL*, the r^2 values of the best performing regression models are rather low (< 0.50) indicating that the two baseflow prameters are not easily related to the current available catchment descriptors.

7.4.4 Initial baseflow (BF_0)

Predictor equations for initial baseflow (BF_0) have been derived using regression analysis. In contrast to the modelling of the ReFH model parameters, initial baseflow is available for each individual flood event. Incorporation of seasonality in the design package has led to seasonal relationships being derived for initial baseflow in addition to a single general relationship using all events. From the 101 catchments analysed, initial baseflow values have been recorded for 1199 events of which 765 events occurred between 1st November and 30th April i.e. winter and 435 in summer. The independent variables included in the analysis are those listed in Table 7.1, and in addition, maximum soil moisture content (C_{max}) and initial soil moisture content (C_{ini}) were used. Estimates of C_{ini} were available for each individual event. The regression analysis was performed in natural space for each group and no weighting was applied to the dependent or independent parameters.

The parameter BF_0 is normalised by dividing through by *AREA* to produce a specific baseflow ($SpBF_0$) which forms the dependent variable. A scaling factor of 10^5 was also applied so the dependent variable, $SpBF_0$ can be expressed as:

$$SpBF_0 = BF_0 / (AREA \times 10^5) \tag{7.9}$$

Once again regression models of all possible parameter combinations were tested, however because of the large number of data points the search was restricted to combinations of up to six explanatory variables. This limit had little impact since negligible improvement was seen for equations containing more than two variables. The best performing models for each analysis (Eq, 7.10, 7.11 and 7.12) i.e. using all events, winter events and summer events, respectively, have been rearranged to express initial baseflow. These were the best performing equations in each analysis. Considering the coefficient of determination, the annual case (r^2 = 0.40) represents a compromise between the summer and winter situation with a slightly better performing model (r^2 = 0.44) for the winter situation and worsening in the summer case (r^2 = 0.32).

$$BF_{0,ALL} = \left(41.36(C_{ini} - 115.89) + 4.56SAAR\right)10^{-5}AREA \tag{7.10}$$

n=1183, r^2 = 0.45

$$BF_{0,WINTER} = \left(63.79(C_{ini} - 120.79) + 5.54SAAR\right)10^{-5}AREA \tag{7.11}$$

n= 752, r^2 = 0.47

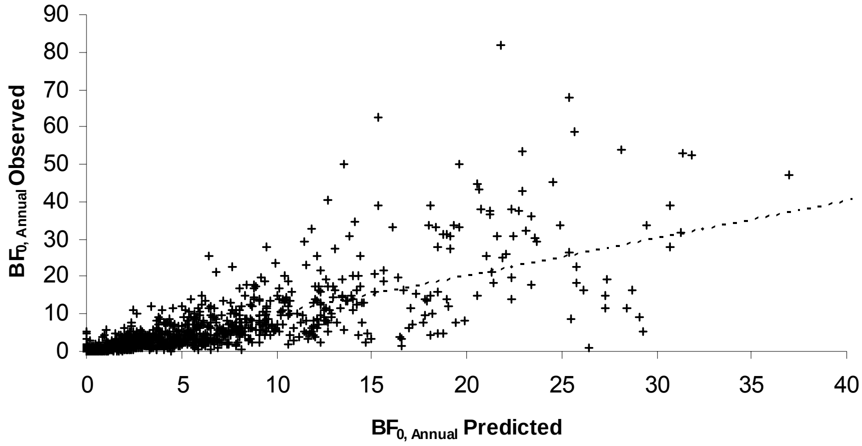
$$BF_{0,SUMMER} = \left(33.94(C_{ini} - 85.42) + 3.14SAAR\right)10^{-5}AREA \tag{7.12}$$

n=431, r^2 = 0.42

Table 7.7 Regression coefficients and statistics for the models predicting initial baseflow

SpBFo	Variable	r^2	Adj.r^2	Coeff.	Standard error of coefficient	t-statistic
All	Constant *CWI* *SAAR*	0.45	0.45	-4793.1 41.4 4.6	269.4 2.6 0.2	-17.79 16.18 27.94
Winter	Constant *CWI* *SAAR*	0.47	0.47	-7705.1 63.8 5.5	570.5 5.5 0.2	-13.51 11.58 25.42
Summer	Constant *CWI* *SAAR*	0.42	0.42	-2899.2 33.9 3.1	297.8 3.3 0.2	-9.74 10.17 13.76

n_{ann} = 1183; n_{winter} = 752; n_{summer} = 431



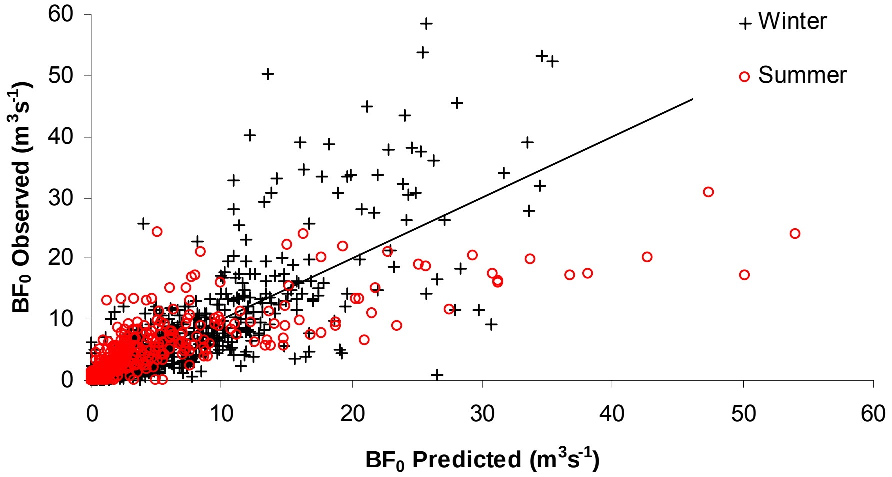


Figure 7.5 Predicted values of initial baseflow for (a) annual (b) summer and winter

The model for estimation of initial baseflow using all events Eq. (7.10) has been included to facilitate a comparison with the results reported in FEH. However, Eq. (7.10) will not be used for any practical purpose in this study. The newly developed models for estimating initial baseflow on a seasonal basis are considered important components in the move towards a seasonally based method as represented by the ReFH model.

It should be noted that when using these equations, as for the FSSR16 equation, it is sometimes possible to obtain negative values for BF_0, in such cases zero should be used instead.

7.5 Summary

To enable the application of the ReFH rainfall-runoff model at ungauged sites, a set of regression models have been developed linking the four ReFH model parameters plus seasonal initial baseflow to readily available catchment descriptors.

The model for predicting *Tp* at an ungauged site developed in this study is comparable to the corresponding models reported in FSR and FEH as they were based on the same set of catchment characteristics and a similar set of catchment descriptors, respectively. It should be noted that the number of catchments used in this study is smaller than in the FEH, leading to an increase in the uncertainty of the estimates obtained at ungauged sites. However, the introduction of a more rigorous procedure for including catchments in the analysis (a minimum of five of which at least one is larger than QMED, Section 4.1) and the joint consideration of all events available on each catchment simultaneously in the parameter estimation procedure will potentially have decreased the sampling uncertainty of each individual *Tp* value, thereby reducing the prediction uncertainty. A more in-depth analysis of the prediction uncertainty and the different sources of uncertainty are considered beyond the scope of this study.

As the loss model developed in this study is structurally different from the loss model concept used in FEH, a direct comparison between the two loss models cannot be made. However, some common characteristics should be noted. It is important to realise that the concept of Percentage Runoff (*PR*), forming an integral part of the FEH methodology, is no longer applicable in the form of a single parameter. Instead of a direct link between S*PR* and a set of catchment descriptors (FEH), this study has formed a relationship between the loss model parameter C_{max} and two catchment descriptors *BFIHOST* and *PROPWET* which then feeds back into the generic loss model described in Eq. (3.3). The generic loss model then further requires an estimate of the initial soil moisture content (C_{ini}) and the rainfall depth (*P*). When comparing the requirements of the generic loss model with the FEH loss model, it can be noted that these requirements are also present in the FEH model. Note that instead of C_{ini} the FEH loss model uses the equivalent *CWI*. The most significant differences in terms of information requirements are that the FEH model is based on *SPRHOST* whereas the ReFH model uses *BFIHOST* and that the *URBEXT* term is now omitted from the ReFH loss model. Using *BFIHOST* rather than *SPRHOST* is considered an improvement as *BFIHOST* is based on a more comprehensive data material (daily runoff) which is much more widely available than the limited hourly event data used for estimation of *SPRHOST*.

A subsequent investigation showed that the adopted regression model for predicting C_{max} has a tendency to underestimate C_{max} in catchments where a large C_{max} value had been observed. This is an indication of the ReFH model's difficulty with modelling of flood events in baseflow dominated and permeable catchments. No solution to this problem was identified in this study and users are recommended to be cautious when applying the model to this type of catchment.

The ReFH baseflow model is another significant structural improvement over the FEH model introduced in this study. Again, this makes a direct comparison between the FEH and the ReFH difficult. However, the initial baseflow derived in this study using all available events correspond well to the baseflow value used in FEH; again C_{ini} corresponds to *CWI* in FEH. Small improvements in prediction of initial baseflow were obtained by considering two seasonal baseflow situations rather than a single relationship.

The baseflow recharge (*BR*) and baseflow lag (*BL*) are new parameters introduced in this study and, therefore, no previous attempt to link these parameters to catchment descriptors have been reported. For both parameters only a weak relationship between observed parameter values and catchment descriptors were identified, making estimates at ungauged sites relatively uncertain. In addition, a tendency for the regression models to underestimate the two model parameters where high values had been observed is evident. Further investigations will be required to identify the exact reasons but, as for C_{max}, the problem might be related to the problem of reduced model performance of the ReFH model on certain types of catchments.

8. Testing and Validation

This chapter contains two independent validations of the developed package for design flood estimation. The first test is based on model performance at two gauged sites. The second test is concerned with assessing the methodology at ungauged sites.

8.1 Introduction

To assess the performance of the ReFH design model, two independent tests were carried out. In both tests the flood frequency curve (FFC) derived using the ReFH model at the site of interest is compared to the FFC derived through a pooled statistical analysis based on AMAX data made available from the HiFlows-UK project. In the first test the ReFH design model is applied to a set of catchments not included in the model calibration but where sufficient observed flood events are available for estimation of the four ReFH model parameters. The second test focuses on the ability of the design method to derive FFC at ungauged sites, i.e. sites where no observed flood events are available and the four ReFH are estimated based on catchment descriptor. In Chapter 5 a set of predictor equations were developed, enabling estimation of the four ReFH model parameters at ungauged sites through knowledge of the catchment descriptors alone.

$$
\begin{aligned}
BL &= 25.47\,BFIHOST^{0.47}DPLBAR^{0.21}PROPWET^{-0.53}\left(1+URBEXT\right)^{-3.01}\\
BR &= 3.75\,BFIHOST^{1.08}PROPWET^{0.36}\\
C_{\max} &= 589.0\,BFIHOST^{0.94}PROPWET^{-0.26}\\
Tp &= 1.492\,PROPWET^{-1.24}DPLBAR^{0.66}\left(1+URBEXT\right)^{-5.02}DPSBAR^{-0.36}
\end{aligned}
\qquad (8.1)
$$

The validation exercise will illustrate how well the ReFH design model can be expected to work when applied to gauged and ungauged catchment in the UK.

8.2 Validation at gauged sites

To enable validation of the ReFH model, two catchments where sufficient observed flood events are available were left out of the list used for development and calibration of the ReFH design model. These catchments can now be used in an independent test of the ReFH design model. A summary of the available flood events for each catchment are shown in Table 8.1.

Table 8.1 Summary of gauged validation catchments

Catchment	AREA (km^2)	No. events	No. events > QMED
48004	25.3	11	4
71003	10.6	17	5

For each catchment, the four ReFH model parameters were calibrated by considering the site being gauged and ungauged. When the site is considered gauged, the parameters are estimated using the procedure outlined in Section 4.1, i.e. firstly the two baseflow parameters *BL* and *BR* are estimated by modelling the recession part of each individual event followed by using an optimisation procedure estimating C_{max} and *Tp* by considering the goodness of fit of all events simultaneously. When the site is considered ungauged, the model parameters were estimated through Eq. (8.1). The resulting model parameters are shown in Table 8.2.

Table 8.2 ReFH model parameters for validation catchments

Catchment	*BL* (hours)		*BR*		C_{max} (mm)		*Tp* (hours)	
	G	*U*	*G*	*U*	*G*	*U*	*G*	*U*
48004	69.5	40.9	1.37	1.33	360	378	4.12	2.23
71003	18.2	23.4	0.63	0.77	324	200	1.33	2.58
G / U = gauged / ungauged								

Using model parameters listed in Table 8.2, the ReFH design model can be applied to derive a FFC for each catchment which can be compared to observed AMAX events, and pooled analysis as shown in Figure 8.1.

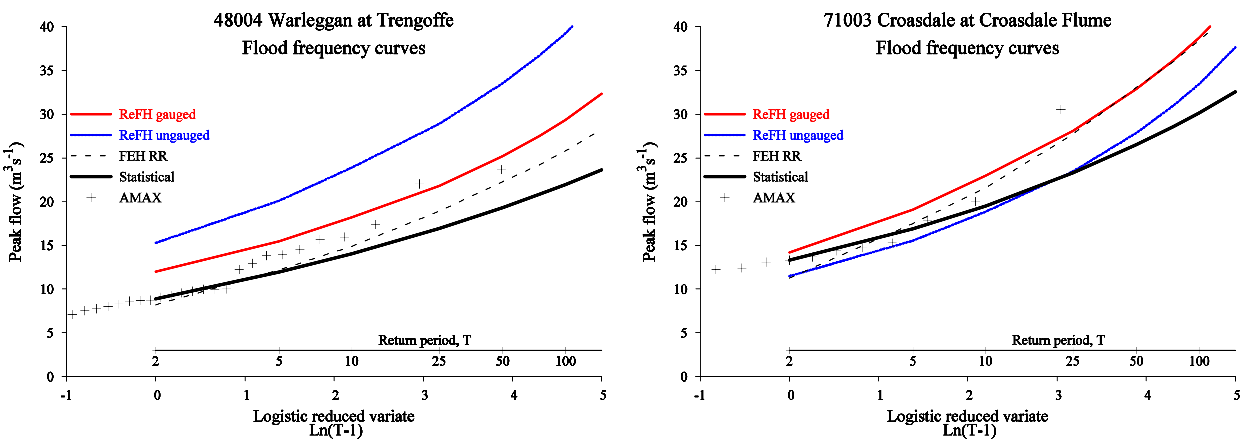


Figure 8.1 Comparison between FFC derived from observed AMAX series (crosses), ReFH at gauged site (red), ReFH at ungauged site (blue), FEH statistical method (solid black) and the FEH rainfall-runoff method at a gauged site (dashed black)

Note that gauging station 71003 is not included in the HiFlows-UK data set and the FFC derived using the statistical method is based on the original FEH AMAX data. The FFCs for the FEH Rainfall-Runoff method have been derived using parameter values of *Tp*, *SPR* and *BF* derived based on analysis of observed flood events as reported in FEH Vol. 4, Appendix A. In both cases the calibrated FEH rainfall-runoff method appears to perform rather well, though consistently overestimating design flood when compared to the statistical method. For both catchments, the ReFH model generates FFC that are comparable with the FFC from the statistical method and the AMAX events themselves.

8.3 Validation at ungauged sites

To assess the performance of the ReFH design model when applied to an ungauged site, the method was applied to 776 catchments located throughout the UK where AMAX data from the HiFlows-UK project as well as catchment descriptors were available. Only catchments with an *AREA* less than 750km^2 have been included in the analysis, reducing the total number of catchments included to 683. At each site the parameters of the ReFH model were estimated through Eq. (8.1) and the design model, as outlined in Chapter 7, applied to derive the hydrograph for a range of return periods. The peak flow of the T-year hydrographs are compared to the corresponding estimate of the T-year peak flow obtained through a pooled statistical analysis at each site, where the index flood is estimated through the AMAX data available at each site under consideration.

The comparison was made for the following return periods: T= 5, 10, 25 and 100 years. The comparison is expressed as the percentage deviation of the ReFH estimate of the T-year peak flow ($Q_{T,ReFH}$) from the corresponding estimate obtained through statistical analysis ($Q_{T,Stat}$), i.e.

$$\frac{\left(Q_{T,ReFH} - Q_{T,Stat}\right)}{Q_{T,Stat}}100\% \qquad (8.2)$$

and the results are shown in Figure 8.2 To Figure 8.5.

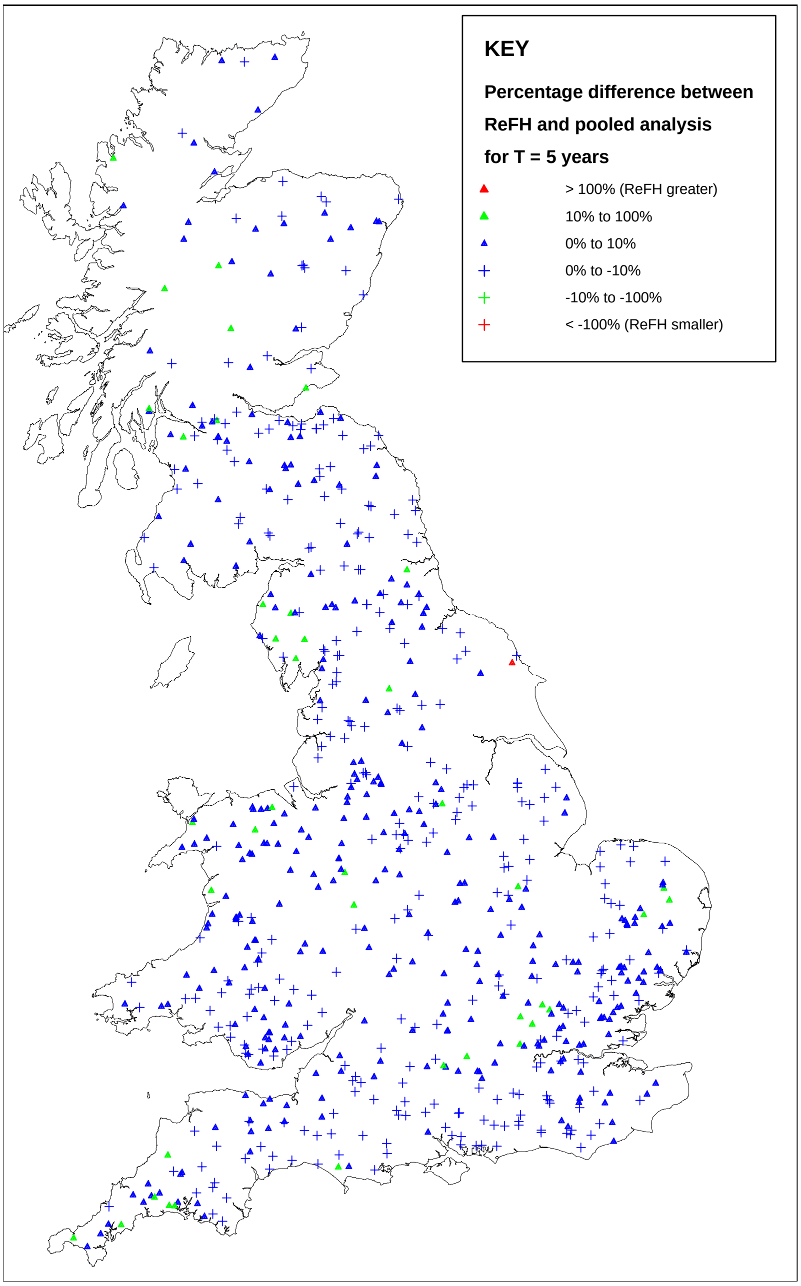


Figure 8.2 Comparison of the 5 year event estimated using ReFH at an ungauged site compared to the corresponding estimate from pooled statistical analysis at the same gauged site

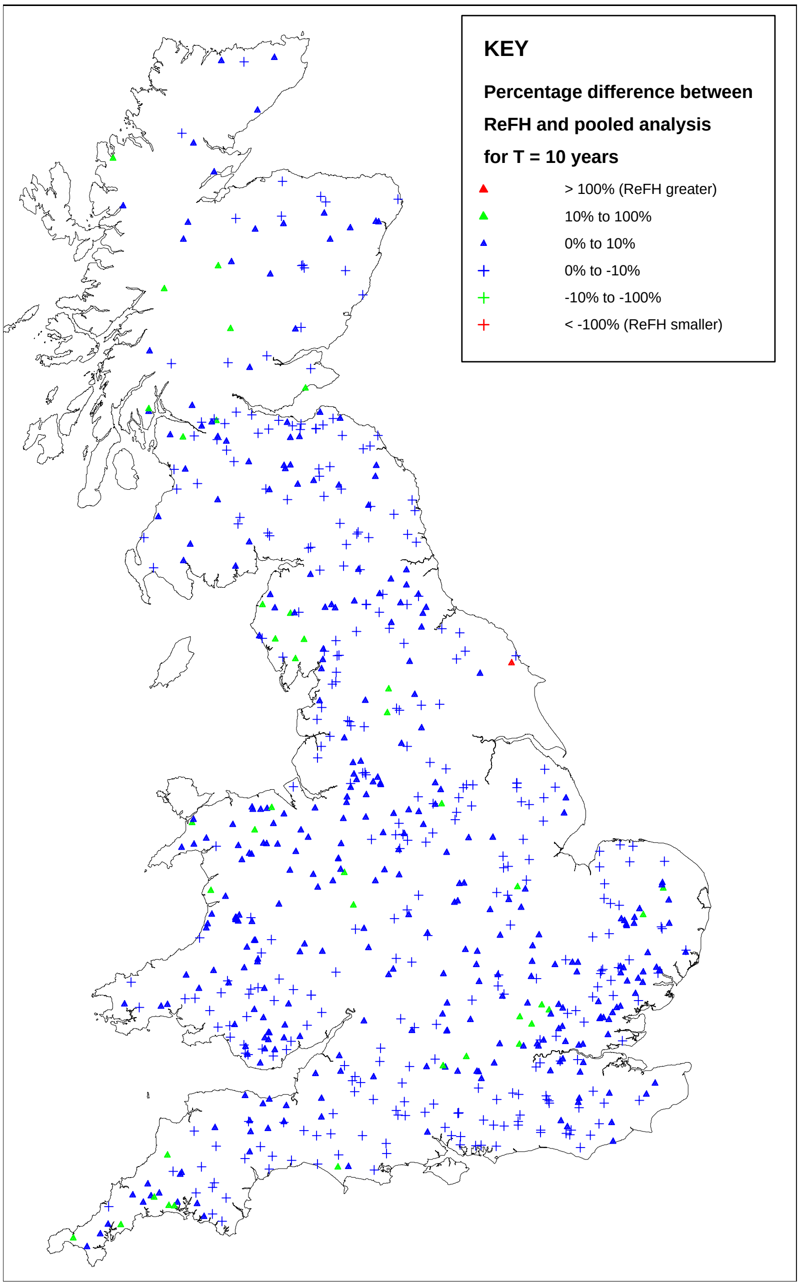


Figure 8.3 Comparison of the 10 year event estimated using ReFH at an ungauged site compared to the corresponding estimate from pooled statistical analysis at the same gauged site

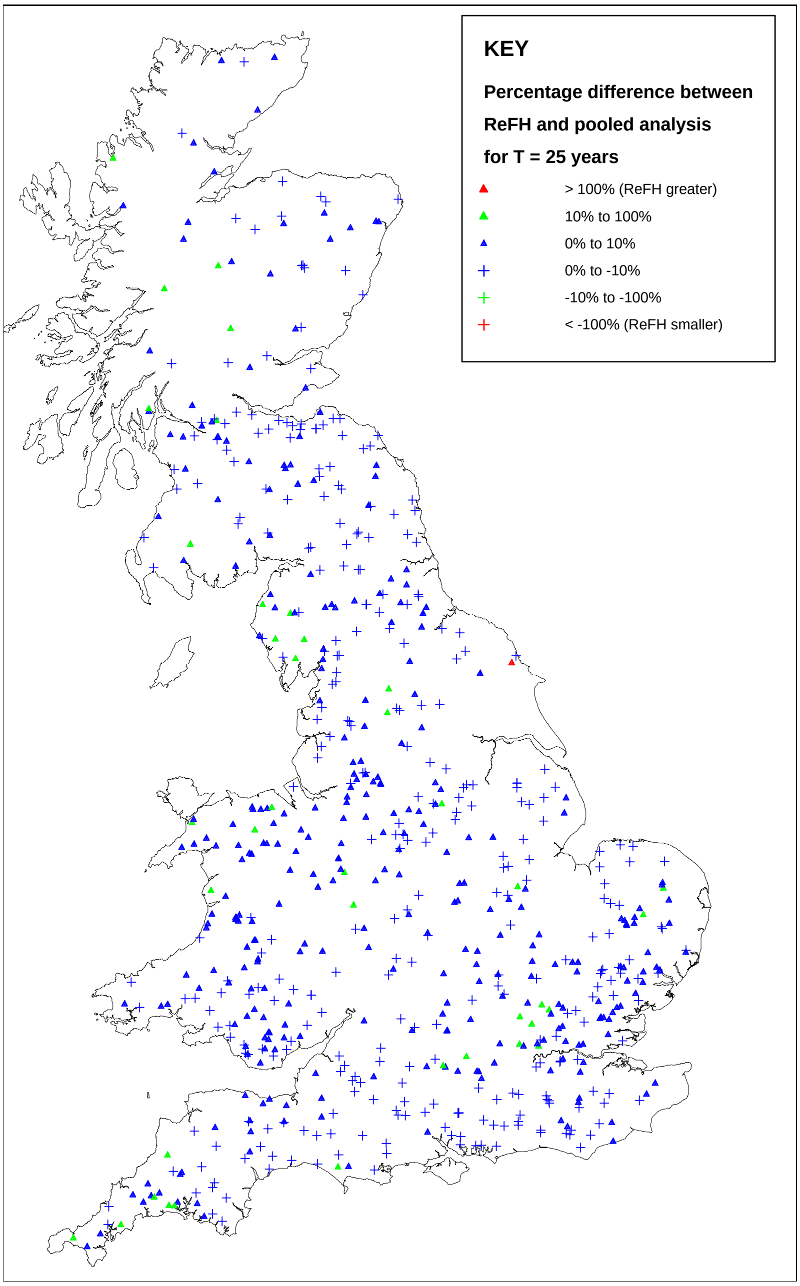


Figure 8.4 Comparison of the 25 year event estimated using ReFH at an ungauged site compared to the corresponding estimate from pooled statistical analysis at the same gauged site

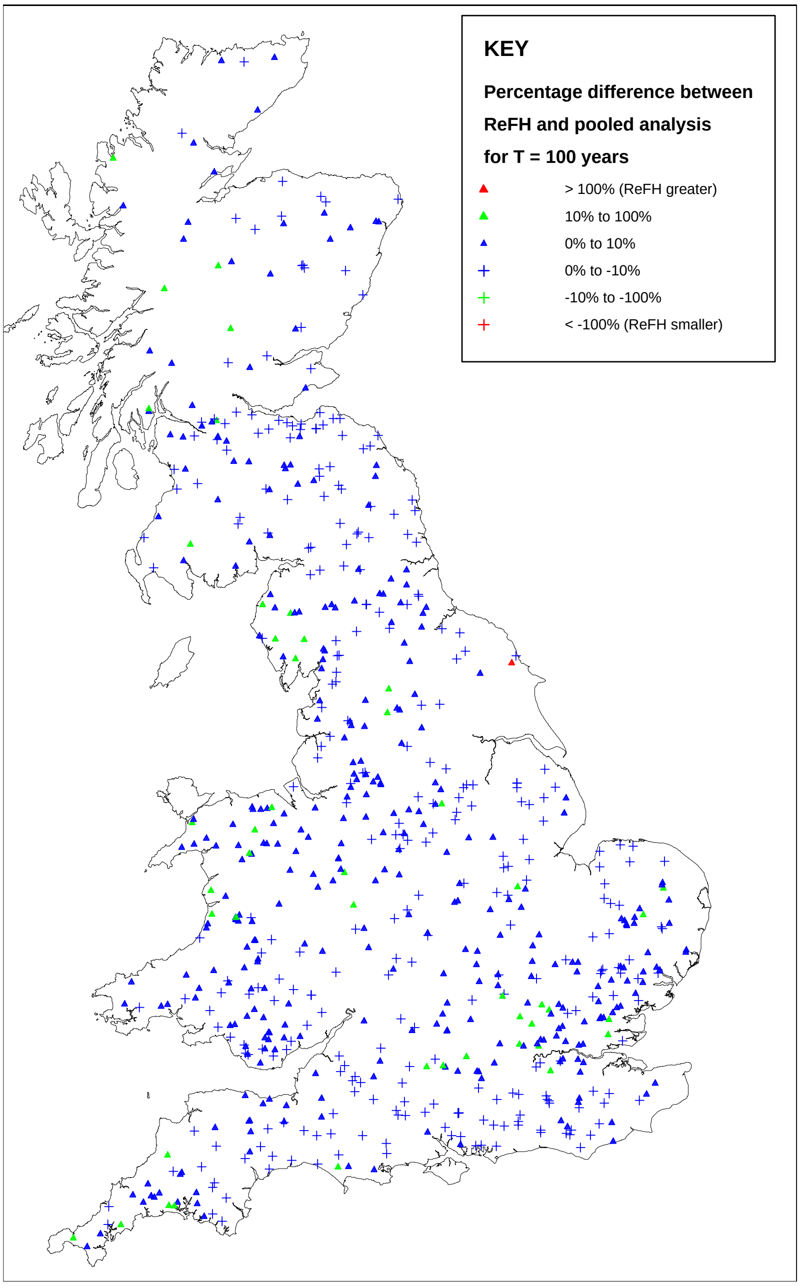


Figure 8.5 **Comparison of the 100 year event estimated using ReFH at an ungauged site compared to the corresponding estimate from pooled statistical analysis at the same gauged site**

At the majority of the selected sites the peak flow value estimated by the ReFH design model is within ±10% (all the blue symbols in Figures 8.2 to 8.5) of the corresponding estimate obtained from the pooled statistical analysis. These results are encouraging and show the ReFH design model can, in general, be expected to perform reasonably well on a variety of different catchments. However, in certain geographic areas the ReFH design model appears to produce estimates that are consistently higher than the corresponding estimates obtained from the pooled analysis. Most notable are highland areas such as North Wales and the Lake District in North West England, but also the highly urbanised area around London in South East England shows signs of consistently higher estimates.

For all return periods, the results obtained for gauging station 27032 Hebden Back at Hebden shows a percentage difference between the peak flow derived ReFH and the pooled statistical analysis, respectively. This particular catchment was highlighted in the FEH Vol. 3 (Robson and Reed, 1999) as being an "unusual catchment". A closer inspection of the AMAX event reveals relatively low values (QMED = $3.64m^3s^{-1}$) for a $22km^2$ catchment. On the other hand, the *BFIHOST* value for the catchment is 0.251, resulting in a high percentage runoff in the ReFH model.

The FEH recommends the use of local observed data to adjust the estimates obtained at ungauged sites using catchment descriptor equations such as Eq. 8.1. The criteria for the selection of suitable donor catchments for the FEH rainfall-runoff method included catchments that were:

- of comparable catchment size;
- within close geographical proximity (since regression errors tends to be spatially clustered);
- rural.

In addition, it was considered preferable to transfer information between catchments within the same river basin if possible.

The effectiveness of data transfer is very much dependent on the second criteria, i.e. the spatial structure of regression residuals of the catchment descriptor equations. As the spatial structure of these residuals has not been investigated in this study, the effect of using donor sites could not be evaluated objectively. It is therefore considered appropriate not to include data transfer from donor sites in the model validation.

8.4 Discussion and conclusions

The results obtained from the two model validation tests are generally very encouraging.

The limited number of catchments with the required number of observed flood events of sufficient data quality meant that most of these catchments were used for calibration of the design model (Chapters 4 to 7), leaving very few for model validation. In fact, only two catchments with observed data were used for model validation, which might be considered too few to draw any firm conclusions.

However, the results obtained for the two catchments point towards an improvement in model performance when observed data are used for calibration of the ReFH model.

In both cases the FFC derived using the ReFH design model is located above the corresponding FFC obtained through pooled statistical analysis (Figure 8.1). Considering the results obtained in the second test, this is believed to be a reflection of the location of the two validation catchments rather than being related to the use of observed data for model calibration.

Applying the ReFH design model at ungauged sites where the ReFH model parameters are estimated using catchment descriptors through Eq. (8.1), the model produced, in general, estimates within ±10% of the corresponding estimates obtained from the statistical analysis. Considering the relatively large prediction uncertainties associated with Eq. (8.1) this result indicates that the ReFH model is robust and can be expected to perform reasonably well on a large number of catchments throughout the UK.

However, the ReFH design model appears to give higher estimates than the statistical method in certain geographic locations, notably North Wales, the Lake District and the South East of England around London. The exact reasons for these relatively higher estimates are not known at present but can be caused by several factors. Using the pooled statistical analysis as the yard-stick against which the performance of the ReFH design model is assessed is a subjective choice. If, for some reason, the pooling group method is found to give less steep FFC for certain types of catchments, this would appear as if the ReFH model gives estimates that are too high. Such cases could, for example, include small urbanised catchments (where there may be relatively few catchments suitable for the pooling) and also catchments where the response to runoff may be quite specific to that particular catchment or sub-catchment type, such as those with a high proportion of chalk or boulder clay where site growth curves may be steep. (Peter Spencer, pers. comm., 2005).

Another reason for the apparent localised discrepancies could be the limited sample of catchments (100) included in the calibration of the ReFH design model. It is likely that some types of catchments were under-represented or not included at all. This is especially the case for urbanised catchments where only seven catchments were available.

9. Conclusions and recommendations

The event-based method for design flood estimation outlined in the Flood Studies Report and, subsequently, in the Flood Estimation Handbook has undergone a radical revitalisation and the outcome is a new improved method for use in the UK as presented in this report. The project focused on the key aspects of data availability, rainfall-runoff model development and recalibration of the design model and each of these has contributed to the final model. Another major improvement is the introduction of a more comprehensive consideration of the seasonal variation of flood-generating mechanisms than was available in the FSR method, including methods for deriving seasonal maximum rainfall, seasonal initial baseflow and seasonal design soil moisture conditions.

9.1 Data collection

As part of this study, the existing Flood Event Archive (FEA) held at CEH Wallingford was updated with catchment average rainfall and river flow data for a number of recent and relatively large flood events. The inclusion of these events significantly increased the total number of events with peak flow exceeding QMED that were available to the analysis, which has, in turn, increased confidence in the model's ability to represent the characteristics of large events. The effort required for collecting, quality checking and systematically archiving the observed flood events was considerable, but was of vital importance to the subsequent analysis and has allowed significant improvements to be made to the tools available for design flood estimation in the UK. Potential problems concerning the lack of suitable data highlighted in the course of the project included the availability of very large events and events from urbanised catchments. Despite the data collection effort, only 20 flood events were identified as having a return period (in terms of peak flow value) larger than 20 years. Therefore it should be recognised that when using the model to estimate design floods with high return periods, the results will inevitably be based largely on extrapolations of model performance at significantly lower return periods. The problem relating to the lack of observed flood events available from urbanised catchments is discussed later.

9.2 Rainfall-runoff model development

In the FSR method, the transformation of rainfall into runoff was accomplished through a rainfall-runoff model consisting of three sub-models: a loss model, a routing model and a baseflow model. This basic structure has been retained in the ReFH model, but each of the three submodels has undergone significant changes and an increased emphasis has been placed on the introduction of a more physically based approach to flood modelling.

The FSR loss model was based on a regression equation linking percentage runoff obtained from an analysis of observed flood events to a set of catchment descriptors, initial soil wetness and rainfall amount. In contrast, the loss model in the ReFH model is based on the well known and widely applied PDM model and introduces a more process oriented approach to hydrological modelling. Notably, the analytical form of the loss model in Eq. (3.3) bears some resemblance to the more empirical FSR model, as in both cases the hydrological losses depend on initial soil moisture and rainfall depth. A further advantage of the ReFH loss model is that losses are calculated successively throughout the storm, rather than being assumed to be constant as in the FSR design model. In fact, the FSR recommends calculating successive losses when analysing observed events, but using a constant loss when modelling design events. The ReFH model therefore provides a more unified approach to losses than the FSR model. Furthermore, the use of a physically based analytical loss equation abolishes the use of the term percentage runoff, which is a subjective term depending heavily on the adopted baseflow separation technique.

The use of the unit hydrograph method for routing the excess rainfall to the catchment outlet has been retained in the ReFH model. The shape of the instantaneous unit hydrograph (IUH) was specified as a kinked triangle defined by three parameters. Through an exploratory data analysis, it was found that the height and the degree of kink of the IUH shape could not reasonably be linked to the available catchment descriptors and was therefore fixed using constant values for all catchments. By fixing the parameters, the model has lost some degree of flexibility in modelling observed events but this was considered a reasonable trade-off for the lack of predictability of the parameters. Consequently, the routing model is described by a standard IUH shape which is scaled to the catchment of interest through a time to peak parameter, and thus is similar to the procedure used in the FSR method. It should be noted that the numerical values of the *Tp* parameter used in FSR differ from the values used in ReFH as the shape of the IUH has changed.

The constant baseflow value added on to the direct runoff in the FSR model has been replaced by a more physically based baseflow model in the ReFH model. The new and improved baseflow model is based on the contributing area concept and has two parameters representing the recharge and the baseflow lag (i.e. the time from recharge to outflow).

9.3 The ReFH design model

The structure of the ReFH design model differs from the FSR design model on two major issues. Firstly, the introduction of seasonal design input values of the boundary conditions (rainfall, initial baseflow and initial soil moisture content) has potentially increased the physical basis of the design model and thereby reduced the need for calibration of the model, though not done away with it completely. Secondly, the ReFH design model was developed to ensure compatibility with other hydrological design methods used in the UK. Therefore, it was decided at the outset that in the ReFH design method, the T-year design flood should be generated by the corresponding T-year design rainfall event. This is considered an important step away from the current practice where, for example, the 100-year flood is assumed to be generated by the 140-year design storm.

The design model was calibrated by matching the peak flow values generated by the ReFH model to the corresponding design flood estimates obtained from a pooled statistical analysis of AMAX series at each of the 100 considered catchments. By fixing the return period of the generating design storm, the initial soil moisture content was used as the free variable to ensure the correct magnitude of the peak flow of the design hydrographs. The method for calculating storm profiles and areal-reduction-factors was retained in the ReFH design model as specified in the FSR.

The design soil moisture content required for reproducing the 5-year peak flow magnitude was adopted as the design initial soil moisture content in the ReFH model. These design values of initial soil moisture content were broadly comparable to the initial soil moisture observed for the largest events analysed from the FEA. This further emphasises the added physical plausibility of the ReFH model over the FSR model.

During the course of the research it became apparent that the growth curves of the FEH DDF model were, in general, steeper than the flood growth curves obtained through pooled analysis of AMAX series. When imposing the FEH design rainfall on the ReFH rainfall model and aiming to produce peak flow values corresponding to the pooled flood frequency curve, this will lead to an increasing discrepancy at higher return periods. To ensure the ReFH design model yield hydrographs with peak flow values corresponding to the pooled statistical analysis it was considered necessary to introduce a calibration parameter in the ReFH loss model. The numerical value of this calibration parameter was related to the considered return period.

Following on from the development, calibration and validation of the ReFH design method, a number of issues should be considered when applying the method.

- The design model has been calibrated up to a return period of 150 years. For return periods in excess of 150 years, no calibration and validation has been carried out.

- Problems of calibrating the ReFH model to observed data from permeable catchments were encountered, where the calibration procedure resulted in very large soil depths (large C_{max} values) to get sufficiently large losses. These very large values of C_{max} were considered unrealistic and, thus, care should be exerted when estimating model parameters on this type of catchment.

- The largest catchment used in the calibration of the ReFH design model is 511 km^2. In the validation of the method, the method was found to perform reliably for catchments up to 750 km^2. No validation of the method on catchments larger than 750 km^2 has been carried out in this study.

Similar to the FSR/FEH rainfall-runoff method, users should also be aware of the limitations and uncertainties associated with the development of a generalised procedure. Examples include the use of simplified rainfall profiles, an areal reduction factor independent of location and return period and the uncertainties (both model and sampling uncertainties) associated with the catchment descriptor equations used for estimating model parameters at ungauged sites.

9.4 Issues for further research

The ReFH model is considered a significant step forward in terms of developing a more physically-based approach to design flood estimation in the UK. The method has been developed by introducing new models and concepts, but has also retained some of the original features of the FSR method. The validation of the design model on both gauged and ungauged catchments showed that the ReFH design model can be expected to perform relatively well on most catchments in the UK. However, the research did highlight a number of areas where the new framework could potentially benefit from further research, and these areas are listed below.

Urban catchments
The development of the design package considered ‘summer’ and ‘winter’ catchments based on the degree of urbanisation as outlined in FEH. This definition was adopted because of the lack of any better method for distinguishing between catchments prone to summer and winter flooding (Bayliss and Jones, 1993). However, since only seven out of the 100 catchments available fell into the summer category, further research should be undertaken into the applicability of the ReFH model to urban catchments.

Volumes in design floods
The only criterion applied in the development of the design procedure was the matching of the peak flow values. Future research into the event-based method for design flood estimation could potentially benefit from taking into consideration the volume of the flood event as well as the peak flow. However, such an approach would require a method for assessing the volume of design floods independently. This could potentially be achieved through a statistical frequency analysis of flood volumes.

Seasonality
The added focus on modelling physical processes conceptually has provided a more suitable framework for introducing some seasonally-varying input parameters into the method of design flood estimation. Indeed, the increased emphasis on the seasonality of the flood-generating mechanisms introduced in this study is considered to be a significant contribution to the design flood event methodology.

The seasonally-varying input parameters used in this study were developed to provide users of the methodology with a practical tool. However, further research could beneficially be targeted at a more comprehensive investigation, particularly at the development of a seasonal maximum rainfall model. In this study, the seasonal design rainfall is derived by multiplying the estimate of the design rainfall obtained from the FEH DDF model (derived from annual maximum rainfall series) by a correction factor, depending on the *SAAR* of the considered catchment, but independent of the considered return period. These simplifying assumptions (with the associated loss of precision) were introduced to reduce the complexity of the problem into a practical tool. However, a more comprehensive study would be needed to develop a seasonal DDF model through an extreme value analysis of seasonal maximum series similar to that conducted to develop the FEH DDF model presented in FEH Vol. 2 by Faulkner (1999). Defra has recently commissioned a project relating to reservoir safety which will be analysing seasonal rainfall frequency for return periods of more than 100 years (Project WS194/2/39).

Apart from rainfall depth this study did not consider seasonality in any of the other design rainfall properties. In fact, storm duration, the storm profiles and the areal reduction factors were adopted unchanged from the FSR study. Further model development could potentially benefit from a systematic study of these properties, taking advantage of the modelling framework developed in this study, as well as the additional data material collected since the development of these tools in the early 1970s. Another potential route for increasing the performance of the ReFH model would be to investigate the possible seasonal variation of the ReFH model parameters, especially the baseflow parameters *BL* and *BR*.

9.5 User acceptance

Since its original publication 30 years ago, the FSR method has been updated through numerous subsequent studies and a large and very experienced user community now exists. Therefore, it is possible that widespread familiarity with the concepts and outputs of the FSR rainfall-runoff method could act as a barrier to initial acceptance of the ReFH model. However, the concept of the ReFH model is based on a more process-orientated approach to flood hydrology and a more fundamental understanding of these issues can only lead to improved hydrological design practice in the UK.

Furthermore, the method is supported by a software implementation of the ReFH design model in a Microsoft Excel spreadsheet, which can be downloaded from the FEH homepage (www.ceh.ac.uk/feh) free of charge. It is anticipated that this software application will facilitate the uptake of the ReFH design method. Furthermore, the Environment Agency has funded CEH to undertake a project entitled *Dissemination of the FSR/FEH rainfall-runoff method* (Project SC040029). The aim of this project is to deliver a stand-alone software package enabling users to analyse and simulate observed flood events and estimate ReFH model parameters from observed events as outlined in Chapter 4 of the present report. Accompanying the software will be a supplementary report to the FEH Vol. 4, effectively replacing the FSR/FEH rainfall-runoff method with the Revitalised FSR/FEH rainfall-runoff method. The supplementary report will focus on practical aspects of the method rather than detailing research and development issues as in the present report.

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Appendix A The ReFH 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, the 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

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

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.

However, owing to the arbitrary nature of *CWI*, and the fact that the original Estimated SMD (or ESMD) calculations are no longer carried out by the Meterological Office, ReFH has instead adopted the uniform Probability Distributed Model (PDM), (Moore, 1985) for deriving losses.

The uniform PDM assumes soil moisture capacity (C) varies over the catchment, from zero to C_{max}, and each capacity (storage depth) occurs with equal frequency. Thus the maximum mean soil moisture deficit (S_{max}), i.e. totally dry soil, in the catchment is given when all capacities from zero to C_{max} are empty, i.e.

$$S_{max} = C_{max}/2 \tag{A.3}$$

At the start of an event, the initial moisture content (depth) is taken as $C_{ini,}$ such that all areas of capacity less than C_{ini} are saturated, and all areas with a capacity greater than C_1 have a deficit. Thus proportionally $(C_{max}-C_{ini})/C_{max}$ of the catchment shows a deficit, and the deficit ranges uniformly from zero to $C_{max}-C_{ini}$. The mean deficit (S_{ini}) in the catchment can thus be found as:

$$S_{ini} = 0.5\,(C_{max} - C_{ini})^2/C_{max} \tag{A.4}$$

or

$$S_{ini}/S_{max} = (1-C_{ini}/C_{max})^2 \tag{A.5}$$

Any new rainfall depth P will be added to the moisture depth ($C_2=C_{ini}+P$), and ignoring drainage and evaporation from the soil column during rainfall (a short storm), the change in deficit ($\Delta S = S_{ini} - S_2$) may be found from:

$$\Delta S/S_{max} \quad = \quad (1-C_{ini}/C_{max})^2 - (1-C_2/C_{max})^2 \qquad \text{(A.6)}$$

Re-arranging and substituting P for (C_2-C_{ini}) gives:

$$\Delta S/S_{max} \quad = \quad (P/C_{max})(2 - (C_{ini} + C_2)/C_{max}) \qquad \text{(A.7)}$$

Now solving for runoff ($Q = P-\Delta S$) and substituting $S_{max} = C_{max}/2$ gives:

$$Q/P \quad = \quad 0.5*(C_{ini} + C_2)/C_{max} \quad = \quad C_{ini} / C_{max} + P / (2C_{max}) \qquad \text{(A.8)}$$

This equation may be applied sequentially during a storm, or to the overall storm depth. Percentage runoff is seen to depend linearly on the soil moisture content C, which grows linearly with rainfall during a storm.

If the soil storage is filled during an event, the mass balance $C_2=C_{ini}+P$ no longer applies. In this case $C_2 = C_{max}$ and equation (A.8) becomes

$$Q/P \quad = \quad 1 - Cmax\ (1 - C_{ini} / Cmax)^2 / (2P) \qquad \text{(A.9)}$$

As the model (at present) assumes no flux of water out of the soil, equation (A.9) is only relevant for that particular time step where the soil content would have exceeded maximum capacity. In all the following time steps the soil is at full capacity and, hence, Q/P = 1.0, i.e 100% runoff.

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.8) compared with the corresponding terms 0.22 *CWI* and 0.1 P in the original FSR equation for *PR* (=100Q/P) (FSR, Vol. I, eq 6.37) may also be noted, implying a C_{max} value of about 500 mm and a S_{max} of about 250 mm. These values are perhaps higher than expected, but they ignore the effect of the SOIL term in the FSR, and the notional maximum deficit of 125 mm in *CWI* refers to deficit from field capacity (drained soil) rather than total capacity.

Of course, the initial moisture depth C_{ini} will vary from storm to storm. Estimation of C_{ini} using a daily soil moisture accounting model is further described in Appendix C.

Overall the uniform PDM provides a suitable replacement for the obsolete *CWI* model.

Appendix B The ReFH baseflow model

The separation of baseflow is fundamental to defining effective rainfall, the overall duration of quick runoff, and the timebase of the unit hydrograph. A consistent method of baseflow separation is thus important. Various methods have been used in the past, tracing some form of separation from the point where the flood hydrograph starts to rise to a point on the falling limb where quick runoff is considered to have ended. However, defining that point can be subjective.

The FSR identifies the point as four times the event LAG from the end of storm rainfall, where LAG is defined as the time from centroid of rainfall to the time of peak flow (or centroid of peaks in a multi-peaked event). This is intuitively consistent with a UH timebase equal to four times its time to peak (the eventually defined triangular UH has a timebase of 2.5 *Tp*). Difficulties with this procedure occurred when LAG values were affected by small amounts of rainfall occurring after the main storm, sometimes (and sometimes not) causing small peaks in the resultant hydrograph. Rigid application of this rule meant that some storm events had to be suitably edited, or rejected from further analysis. The need for long 'clean' recessions also meant that some artificial method of recession extension was needed to salvage an event that might otherwise have to be rejected because its recession was truncated by the start of even a small following event. Another difficulty noted by Boorman and Reed (1981) involved the individual estimation of LAG for each event, and how the variability this caused was contributing to differences in UH shape between events.

Even without these difficulties it must be recognised that the FSR baseflow separation was not meant to model a process, but to remove a relatively small part of the hydrograph that was largely unrelated to the flood process. In design use, the average baseflow was simply added as a constant flow, contributing in part to the relatively 'unskewed' nature of resultant design hydrographs. However, modelling baseflow becomes more important when assessing flood response throughout a catchment, as for example in a river routing study, a land use impact study, or as part of a Catchment Flood Management Plan. It should also be noted that changes in runoff response in the upper reaches of a catchment are likely to be delayed into the tail of the downstream hydrograph and run the risk of being separated out with the baseflow in any analysis.

For these reasons, a simple baseflow model is included in ReFH, based on the linear reservoir concept and its characteristic recession defined by an exponential decay. The similarity of recession curves to exponential decays has often been noted, and indeed the recession extension method used in FSR is based on a system of linear reservoirs in parallel. However, rather than just curve fitting to extrapolate a truncated recession, the baseflow model in ReFH seeks to link the recessions preceding and following an event by specifying the inputs to the linear reservoir as baseflow recharge. One possible approach would be to define a proportion of rainfall as recharge. In practice, a soil moisture approach might be required, partitioning rainfall into surface runoff, soil moisture, and baseflow recharge. This approach could be explored, but currently a simpler approach is being used which is independent of rainfall.

The model developed in this study is based on work by Appleby (1974), with reference to Wemelsfelder (1963) and Sittner *et al.* (1969) concerning the contributing area concept, and assumes that the saturated area of the catchment that produces surface runoff is the same area that produces baseflow recharge, and furthermore that the ratio *BR* of recharge to runoff is fixed. Unsaturated area produces no recharge as the water is retained as soil moisture. The recharge passes through a linear baseflow reservoir (lag *BL*) before emerging into the same river system that carries the surface runoff. Since in a linear system the order of the routing components is immaterial, the baseflow hydrograph at the catchment outlet can be determined by routing *BR* times the (as yet undefined) observed 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.

Expressing this mathematically for the linear reservoir relating the recharge store contents (*S*) to baseflow (*q*),

$$S = BL\,q \tag{B.1}$$

and substituting this in the continuity equation relating change in storage (*dS/dt*) to the difference between recharge (r) and outflow (q), where recharge is proportional to surface flow, that is *total* flow (*Q*) minus baseflow (*q*), we get

$$dS/dt = BL\,dq/dt \quad = \quad r - q = BR(Q - q) - q \tag{B.2}$$

Re-arranging gives the differential equation

$$\frac{dq}{dt} + \frac{(1+BR)q}{BL} = \frac{BR}{BL}Q \tag{B.3}$$

or

$$\frac{d}{dt}\left(q\exp\left(\frac{t(1+BR)}{BL}\right)\right) = \frac{BR}{BL}Q\exp\left(\frac{t(1+BR)}{BL}\right) \tag{B.4}$$

This can be integrated assuming Q changes linearly over a single timestep Δ, and then expressed in a ‘Muskingum’ form of recurrence relationship as:

$$q_1 = k_1Q_0 + k_2Q_1 + k_3q_0 \tag{B.5}$$

where

$$k_1 = \frac{BR}{(1+BR)}\left(\frac{BL/\Delta(1-C_3)}{1+BR} - C_3\right) \tag{B.6}$$

$$k_2 = \frac{BR}{1+BR}\left(1 - \frac{BL/\Delta(1-C_3)}{1+BR}\right) \tag{B.7}$$

and

$$k_3 = \exp\left(-\frac{(1+BR)\Delta}{BL}\right) \tag{B.8}$$

Thus successive points q_N along the baseflow hydrograph can be determined from the model parameters *BR* and *BL*, a starting baseflow q_0 (usually taken as the total flow before the start of the event) and the observed total hydrograph ordinates Q_N during the event. At each timestep, surface runoff is then obtained as the difference between Q and *q*.

In ReFH, an initial value for 'Baseflow Lag' *BL* can be determined from baseflow recession constant, exp($-\Delta/BL$), fitted to the available recession beyond the chosen end point of quick response runoff; an initial value of the 'Baseflow Recharge' factor *BR* can be optimised such that the derived baseflow hydrograph forms a close match to that same part of the recession. REFH presents a plot of the event and invites the user to select the start and end times of the recession period to fit. This period is split into two sections, with the ratio of mean flow in each section used to estimate the linear recession parameter *BL*. A linear search is then used to optimise the recharge parameter *BR*, minimising the weighted least square error between the observed hydrograph and the modelled baseflow. A weighting factor 2 is applied to the error whenever the modelled baseflow exceeds the observed hydrograph, but otherwise a factor 0 is applied outside the selected recession period. This weighting tends to produce a fitted baseflow that falls below any troughs in a multipeaked event and approaches the selected recession period asymptotically. The user can view the effect of using an alternative *BL* (with a revised optimum *BR*), or of using alternative values of both *BL* and *BR*.

Values of *BL* and *BR* can be assessed for each event, or averaged over a number of events, and then held constant while optimising the effective rainfall and unit hydrograph parameters for each event. Alternatively *BL* and *BR* values can be re-optimised together with the effective rainfall and unit hydrograph parameters, using the predetermined values to define starting values or limits for the optimisation.

This baseflow model has a reasonable theoretical basis, but has been applied as an analytical procedure; the model defines the baseflow and quick response hydrographs, from which effective rainfall can be estimated and the UH derived. However, there are three methods of using the model to assess fitting errors (as in model optimisation):

- the quick response hydrograph can be modelled, and the originally defined baseflow hydrograph can be added.
- a true modelled baseflow can be determined by routing *BR* times the quick response hydrograph through the baseflow reservoir of lag *BL.*

- a modelled total hydrograph can be determined by routing *BR* times the effective rainfall through the baseflow reservoir, combining the outflow with the effective rainfall, and routing the total flow through the UH.

Each of these methods is included in ReFH, but unlike the first method, the second and third do test the combined quick response and baseflow model as a whole, and any lack of fit in the quick response model will be compounded in the estimation of baseflow. The second and third methods are essentially equivalent, as the order in which linear routing models are applied is unimportant. However, the third method is particularly relevant when modelling a catchment as a series of subcatchments. The baseflow parameters can be derived from a downstream hydrograph but applied individually to determine total runoff from each subcatchment on its own.

Appendix C Updating soil moisture for the PDM model

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.

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:

$$\frac{dm}{dt} = f - d - E \qquad \text{(C.1)}$$

This differential equation is developed for three soil moisture zones:

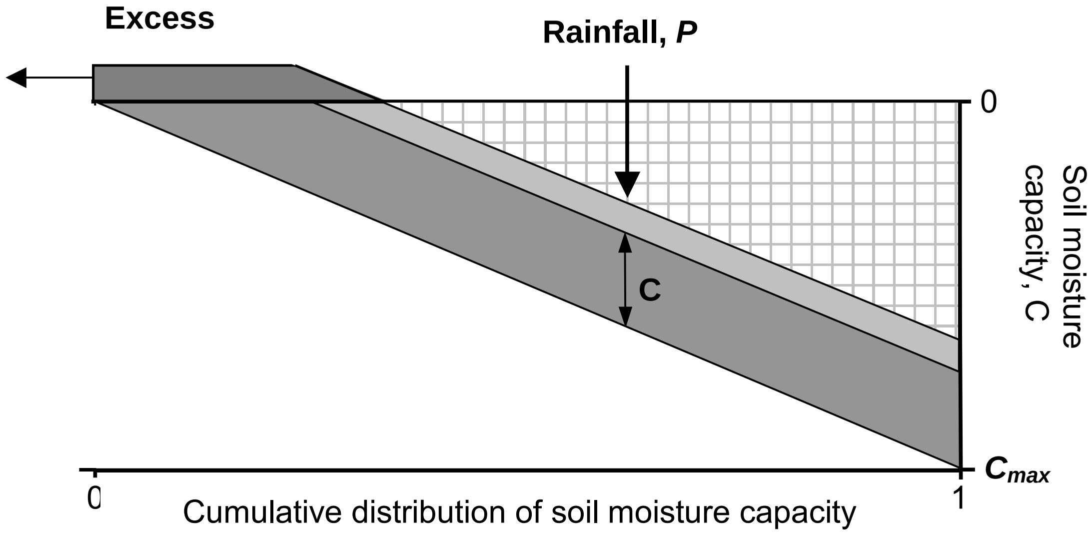
- upper zone, above field capacity *FC*, where drainage *q* depends on moisture content above *FC* $(d=k(m-FC))$, and evaporation is at the potential rate $(E=p)$;
- mid zone, between field capacity *FC* and rooting depth *RD*, where drainage ceases but evaporation stays at the potential rate $(E=p)$;
- 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 $½C_{max}$ and the mean deficit equal to $(C_{max}-c)^2/2C_{max}$. Thus:

$$\frac{m}{SM} = \frac{C_{max}/2 - (C_{max} - c)^2/2C_{max}}{C_{max}/2}$$

or

$$1 - \frac{m}{SM} = \left(1 - \frac{c}{C_{max}}\right)^2 \qquad \text{(C.2)}$$



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

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

The mid zone equation can be obtained by setting k and FC to zero, and the lower zone equation can be ontained 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 C.3 does not exist, but a finite difference solution can be found as:

$$\frac{(m_t - m_0)}{t} = i\left(1 - \frac{(m_t + m_0)}{2SM}\right)^{\frac{1}{2}} - k\left(\frac{(m_t + m_0)}{2} - FC\right) - p \qquad \text{(C.4)}$$

Rearranging to isolate the infiltration term:

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

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

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

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

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

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:

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

with the solution:

$$\begin{aligned} M_t &= \left(G-\left(\frac{i_*}{k_*}\right)^2\right)+\left[\left(G-\left(\frac{i_*}{k_*}\right)^2\right)^2-\left(G^2-\left(\frac{2i_*}{k_*}\right)^2\right)^2\left(1-\frac{M_0}{2}\right)\right]^{1/2} \\ &=\left(G-\left(\frac{i_*}{k_*}\right)^2\right)+\frac{i_*}{k_*}\left[-2G+\left(\frac{i_*}{k_*}\right)^2+4\left(1-\frac{M_0}{2}\right)\right]^{1/2} \end{aligned} \tag{C.9}$$

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 timestep, based on rainfall, drainage and evaporation during the timestep:

$$\frac{m_t}{SM}=\frac{m_0}{SM}\left(\frac{2}{k_*}-1\right)-\frac{E}{k_*}-\left(\frac{i_*}{k_*}\right)^2+\frac{i_*}{k_*}\left[\left(\frac{i_*}{k_*}\right)^2+\frac{4}{k_*}\left(k_*-\frac{m_0}{SM}+\frac{E}{2}\right)\right]^{1/2} \tag{C.10}$$

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 ($FC > m > RD$):

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

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

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

$$\frac{m_t}{SM} = \frac{m_0}{SM}\left(\frac{2}{k_*} - 1\right) - \left(\frac{i_*}{k_*}\right)^2 + \frac{i_*}{k_*}\left[\left(\frac{i_*}{k_*}\right)^2 + \frac{4}{k_*}\left(k_* - \frac{m_0}{SM}\right)\right]^{\frac{1}{2}} \qquad \text{(C.12)}$$

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 timestep, 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 timestep is used up to 9am on the day of the event, and then the equations are solved for a single timestep from 9am to the start time of the event. However, if soil moisture crosses a zone boundary (*RD* or *FC*), the timestep is split and the corresponding zone equations applied to each part. Finally Equation (C.2) is applied to the *m* value at the start of the storm to determine the initial storage depth C_{ini}.

In solving the equations, daily rainfall is found using the full national raingauge network recorded by the Met Office. It is derived as the average from each 1km grid point within the catchment, where the grid point values are estimated from the three nearest raingauges forming a triangle around the grid point. Daily potential evaporation is found as a climatological average sequence fitted to monthly average pe values (1960-90) derived from published MORECS data. A second order Fourier series is fitted to the catchment average pe values found by area weighted average of the MORECS squares falling within the catchment.

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 mm, 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 D The DAYMOD model

In a parallel project to this ‘Revitalisation of the FSR/FEH rainfall runoff model’, a continuous simulation model DAYMOD has been developed to assess the modelling of antecedent condition, primarily for flood modelling in groundwater dominated catchments (Packman, 2004). DAYMOD shares many model concepts and components with the ReFH model described in this report, but it runs at a daily timestep, converting catchment average daily rainfall to mean daily flow. It uses daily data from the Met.Office rainfall archives, and is calibrated against continuous Mean Daily Flow from the National River Flow Archive held at CEH. The good availability and coverage of daily data mean that the model can be applied to many more catchments than is the case for ReFH.

DAYMOD uses the same baseflow model as ReFH (see Appendix B), and includes amongst a range of soil-moisture models, the PDM based model described in Appendix C. It also adopts a unit-hydrograph based surface routing model, but as the work focused on assessing soil moisture models, it uses a simpler linear reservoir form in place of the FSR triangle.

The DAYMOD project found that the PDM soil-moisture model gave the best model fits both during calibration and in ‘split sample’ validation. The other soil-moisture models tried were:

- an extended version of the Met Office ESMD model,
- an extended version of FSR/FEH CWI model, and
- two variants of the PDM model, with the square route relationship between infiltration and soil moisture (see Equation C.3) replaced by (a) a simpler linear relationship (1-*m/SM*), and (b) a square relationship $(1 - m/SM)^2$ equivalent to the well-known SCS runoff model.

It was this work that led to the adoption of the PDM soil-moisture model in ReFH.

Given the broad similarity between DAYMOD and ReFH, when difficulties arose with fitting ReFH to and the short event-recessions available in the Flood Event Archive, an alternative approach was tried using DAYMOD and daily mean flows. Unfortunately, the DAYMOD analysis gave much longer lag values (*BL*). The reasons for this have not yet been fully investigated, but might include (1) reduced recession rates in the long recessions found in continuous flow series, and (2) the infinite tail of the linear reservoir based unit hydrograph (used in place of the FEH triangle) that could be used in DAYMOD to fit the early part of the event recessions, leaving the baseflow model for longer term recession modelling. In any case, as discussed in Section 4.2, the DAYMOD baseflow parameters have not been used in this study, but ReFH has been fitted to each event recession of reasonable length, and the parameters averaged for each catchment.

Although the DAYMOD baseflow parameters have not been used in ReFH, some of the soil-moisture accounting parameters have. As described in section 3.2.4, the soil-moisture model has four parameters: a catchment average soil moisture capacity (*SM*), a field capacity (*FC*) to which soil moisture will drain (decay) under gravity alone, a corresponding daily decay factor (*DK*), and a rooting depth (*RD*) representing the moisture content below which evapotranspiration is attenuated in proportion to moisture content. In practice, *RD* and *SM* have been expressed as multiplying factors (*RD'* and *SM'*) on *FC* (which is taken a storage depth in mm). Thus, during optimisation *RD'* is constrained to an upper limit of less than 1.0 (so soil moisture at the Rooting Depth is less than the drainage limit, Field Capacity), and *SM'* is constrained to a lower limit of greater than 1.0 (so Field Capacity is less than the total available soil-moisture capacity). The distinction between *SM* and *SM'* has not always been made, but it should be clear from the context and values reported.

It should be noted that although *SM* has been defined in different contexts as the maximum soil moisture capacity (from dry conditions) and the maximum soil deficit (from wet conditions), the two maximum values are numerically identical. Moreover, given the assumed triangular distribution of soil moisture capacity over the catchment, the average soil moisture capacity (*SM*) equals half the maximum point capacity (C_{max}) used in section 3.2.1 of the main report. That is:

$$C_{max} = 2*SM = 2 * FC * SM' \qquad \text{(D.1)}$$

It should also be noted that the ratio *FC/SM* (or *1/SM'*) is closely related to Standard Percentage Runoff (*SPR*) used in the FEH.

The four parameters (*SM*, *FC*, *RD* and *DK*) all define how soil moisture, and therefore percentage runoff, vary within the catchment from event to event. With the relatively small number of events available to fit ReFH, successful optimisation of all four soil moisture parameters on each catchment, was always likely to be difficult. Instead, as discussed in section 4.3.1 of the main report, reasonable fixed values of *RD* and *DK* were chosen (0.3 and 0.8 respectively), based on the experience with DAYMOD. However, optimising both *FC* and *SM* still gave some unrealistically high values of *FC*, accompanied by similarly high values of *SM* (so that the ratio *FC/SM* remained fairly constant). It was therefore decided to fix *FC* at the value obtained by DAYMOD, and optimise just the one ReFH soil parameter *SM* (or, in practice, *SM'*).

Given the earlier discussion of how the baseflow parameters in DAYMOD and ReFH were found not to be equivalent, the adoption of the DAYMOD *FC* value might seem unwise. However, it should be noted that fixing either *FC* or *SM* at some suitable value still allows the equivalent 'SPR' to be optimised by adjusting the other parameter.

Before leaving the subject of DAYMOD and the similarity of parameters values with ReFH, mention must be made of DAYFEH (Packman, 2003), a variant of DAYMOD developed to assess the FEH model parameters throughout the Thames catchment. DAYFEH incorporates the triangular unit hydrograph (converted for mean flow rate) along with the FEH Percentage Runoff and Baseflow equations. The FEH parameters *Tp(0)* (Time to peak of the instantaneous unit hydrograph), *SPR* (Standard Percentage Runoff) and *SBF* (Standard Baseflow, m^3/s) were derived using Mean Daily Flow from 31 subcatchments, ranging in area from 50 to 9950 km^2 (where "Standard" relates to a CWI=125). Four of these subcatchments had been used in developing the FEH rainfall-runoff model, and the table below compares the parameters obtained by (1) the FEH analysis, (2) estimation from catchment descriptors, CDs, and (3) by the DAYFEH model.

Table D.1 Comparing FEH derived parameters with those fitted to daily data

Catchment	Area km^2	SBF FEH	Tp(0) FEH	SPR FEH	SBF CDs	Tp(0) CDs	SPR HOST	SBF DAYFEH	Tp(0) DAYFEH	SPR DAYFEH
Cherwell at Banbury	204.3	1.6	19	34.7	4.1	12.2	42.4	0.6	22.3	28.2
Loddon at Sheepsbridge	360.2	3.2	19.3	41.7	7.7	10.8	26.8	1.8	18.9	28.7
Blackwater at Swallowfield	176.6	4.2	11.9	22.3	3.9	11.7	26.4	2.7	25.8	24.7
Cut at Binfield	50.2	1.6	8.1	50.5	1.0	5.9	41.6	0.3	10.4	41

This table shows that the estimates from catchment descriptors can differ considerably from the observed FEH values, but that the DAYFEH values are generally quite similar to the FEH values. For baseflow (*SBF*), the DAYFEH values are smaller than the FEH values, but the impact on flood peaks is minimal. The DAYFEH values of *Tp(0)* are encouragingly similar to the FEH values, especially where values of under 24h have been found using the daily timestep data. This may be attributed to (a) the DAYFEH conversion of the unit hydrograph to reflect mean flow in the timestep, and (b) variability in *Tp(0)* estimation caused by the timing of rainfall during the day being averaged out over the large number of storms modelled in a continuous simulation approach. Only for the Blackwater at Swallowfield is the FEH value of *Tp(0)* significantly shorter than found by DAYFEH, and closer inspection of the FEH results showed that the FEH value related to a much more skewed optimum unit hydrograph shape with a longer timebase (*QpTp*=150, *TB*=58.5h). Only the standard *QpTp*=220 shape has been fitted by DAYFEH, with a timebase of 2.525 *Tp* (i.e. 65.1h) that is quite similar to the FEH value.

Appendix E Details of analysed catchments

Number	Name	*IHDTM*	*NGR*	*AREA*	*SAAR*	*BFIHOST*	*SPRHOST*	*FARL*	*PROPWET*	*DPLBAR*	*DPSBAR*	*URBEXT_1990*
7001	Findhorn at Shenachie	282550	833550	415.87	1217	0.451	55.8	0.992	0.68	25.63	141.77	0.0002
19002	Almond at Almond Weir	300250	665150	44.36	1016	0.364	47	0.998	0.57	10.74	37.76	0.0327
19005	Almond at Almondell	308600	668450	239.27	963	0.362	46	0.957	0.52	16.86	47.69	0.0289
20001	Tyne at East Linton	358950	676650	307.06	713	0.489	35.4	0.991	0.43	25.6	71.45	0.0035
22006	Blyth at Hartford Bridge	424200	579850	264.95	696	0.33	38.6	0.98	0.43	22.96	32.83	0.01
22009	Coquet at Rothbury	406600	601650	345.62	905	0.39	45.5	0.98	0.45	25.88	143.5	0.002
23002	Derwent at Eddys Bridge	404250	550800	117.92	943	0.31	48.1	0.83	0.59	11.31	98.39	0
23006	South Tyne at Featherstone	367150	560950	323.21	1332	0.27	52.9	0.99	0.64	19.58	125.7	0.001
23008	Rede at Rede Bridge	386950	583350	344.98	941	0.32	49.4	0.97	0.47	25.12	96.26	0.001
23010	Tarset Burn at Greenhaugh	378800	587750	95.67	993	0.3	52.6	1	0.56	9.32	87	0
23011	Kielder Burn at Kielder	364400	594600	58.81	1199	0.27	55	1	0.59	7.42	139.66	0
24004	Bedburn Beck at Bedburn	411950	532150	74.11	894	0.36	43.8	0.99	0.59	9.62	109.67	0.001
24005	Browney at Burn Hall	425900	538800	178.29	743	0.33	39.3	1	0.41	19.6	77.88	0.02
24007	Browney at Lanchester	416350	546100	44.66	797	0.33	40.5	1	0.59	8.11	75.2	0.002
25003	Trout Beck at Moor House	375750	533500	11.74	1905	0.22	59.9	1	0.64	3.33	87.98	0
25005	Leven at Leven Bridge	444500	512100	194.54	726	0.38	40.5	0.99	0.34	25.49	75.96	0.01
25006	Greta at Rutherford Bridge	403250	512250	86.92	1125	0.24	55.1	0.99	0.62	12.4	67.67	0.001
25019	Leven at Easby	458550	508550	15.13	830	0.52	38.6	1	0.37	5.3	130.18	0.001
27001	Nidd at Hunsingore Weir	442650	452900	490.49	965	0.4	39.6	0.95	0.37	36.9	77.27	0.02
27026	Rother at Whittington	439250	374250	167.08	811	0.49	27.9	0.97	0.38	10.1	74.68	0.1
27027	Wharfe at Ilkley	411050	448150	447.48	1371	0.36	46.6	0.97	0.62	32.71	139.79	0.002
27034	Ure at Kilgram Bridge	418850	486000	511.32	1336	0.38	46.9	0.99	0.63	32.91	132.03	0.002
28008	Dove at Rocester Weir	411350	339750	401.34	1020	0.55	24.8	0.99	0.41	28.46	114.32	0.003
28026	Anker at Polesworth	426250	303250	370.5	653	0.44	39.5	0.99	0.3	23.6	27.34	0.06
28033	Dove at Hollinsclough	406450	366850	7.96	1346	0.403	42.4	1	0.52	3.23	173.79	0
28039	Rea at Calthorpe Park	407150	284750	73.93	781	0.51	34.9	0.95	0.29	8.12	45.32	0.33
28041	Hamps at Waterhouses	408100	350350	36.87	1085	0.3	47.2	1	0.44	7.68	87.97	0.003
28070	Burbage Brook at Burbage	425850	380250	8.47	1006	0.42	40.2	1	0.38	2.74	87.07	0

Number	Name	*IHDTM*	*NGR*	*AREA*	*SAAR*	*BFIHOST*	*SPRHOST*	*FARL*	*PROPWET*	*DPLBAR*	*DPSBAR*	*URBEXT_1990*
29004	Ancholme at Bishopbridge	503150	390950	58.89	615	0.55	29.4	1	0.26	8.39	11.61	0.004
30001	Witham at Claypole Weir	484250	348150	296.04	615	0.592	28.5	0.979	0.27	27.69	30.94	0.0188
30004	Partney Lymn at Partney Mill	540350	367500	60.11	685	0.57	32.4	0.98	0.29	9.4	54.22	0.01
30017	Witham at Colsterworth	492850	324750	50.18	641	0.65	22.6	1	0.27	7.38	22.59	0.007
31005	Welland at Tixover	496850	299650	419.43	636	0.37	45.1	0.97	0.3	33.92	51.89	0.008
31010	Chater at Fosters Bridge	496100	303100	68.85	640	0.52	33.1	0.99	0.3	10.9	62.65	0.004
32002	Willow Brook at Fotheringhay	506550	293350	94.33	603	0.37	43.2	0.9	0.25	19.92	29.61	0.06
32003	Harpers Brook at Old Mill Bridge	498450	279850	70.57	621	0.41	40.9	1	0.3	12.5	38.28	0.008
32006	Nene/kislingbury at Upton	472250	259100	221.57	651	0.45	42.6	0.98	0.3	19.07	48.17	0.01
34003	Bure at Ingworth	619050	329750	168.09	669	0.779	20.8	0.977	0.31	12.53	23.62	0.0121
34007	Dove at Oakley Park	617400	277050	139.31	585	0.42	37.3	0.99	0.28	14.16	15.43	0.01
35008	Gipping at Stowmarket	605950	257850	127.03	577	0.4	43.4	0.99	0.28	8.8	25.05	0.02
36010	Bumpstead Brook at Broad Green	569050	241800	28	588	0.38	44.6	1	0.27	4.63	34.85	0.006
37001	Roding at Redbridge	541500	188250	301.12	607	0.33	46.6	0.98	0.29	33.67	30.4	0.04
37003	Ter at Crabbs Bridge	578500	210750	77.67	570	0.46	41.8	0.97	0.31	13.33	18.89	0.008
38020	Cobbins Brook at Sewardstone Road	538700	200050	38.74	617	0.22	49.5	0.99	0.29	7.09	45.36	0.03
39005	Beverley Brook at Wimbledon Common	521700	171850	39.63	630	0.47	33.9	1	0.29	7.3	27.16	0.37
39007	Blackwater at Swallowfield	473200	164650	360.19	708	0.63	26.8	0.89	0.32	19.37	32.8	0.06
39012	Hogsmill at Kingston Upon Thames	518350	168700	72.86	671	0.59	27.2	0.99	0.3	10.99	32.76	0.2
39022	Loddon at Sheepbridge	471850	165050	176.58	735	0.59	26.4	0.93	0.33	19.24	33.54	0.04
39025	Enborne at Brimpton	456800	164950	142.1	789	0.5	32.8	0.98	0.32	14.15	54.61	0.009
39052	The Cut at Binfield	485300	171400	50.2	676	0.35	41.6	0.94	0.29	7.62	25.36	0.11
39053	Mole at Horley	527050	143250	91.59	812	0.46	40.3	0.94	0.36	10.52	34.9	0.09
39092	Dollis Bk at Hendon Lane Bridge	524050	189350	23.77	689	0.17	50.5	0.99	0.29	6.33	50.48	0.25
40005	Beult at Stile Bridge	575950	147800	278.04	691	0.35	44.6	0.99	0.34	19.45	27.95	0.006
40006	Bourne at Hadlow	563200	149550	50.3	719	0.62	29.5	0.96	0.36	8.34	65.44	0.02
40007	Medway at Chafford Weir	551600	140650	252.46	830	0.44	42.3	0.93	0.35	14.54	83.94	0.02
40008	Great Stour at Wye	605050	147150	226.43	741	0.65	28	0.98	0.34	18.97	39.87	0.03
40009	Teise at Stone Bridge	571850	140050	134.55	812	0.44	42.6	0.9	0.36	12.69	79.96	0.005
40010	Eden at Penshurst	552150	143850	224.79	742	0.42	41.2	0.92	0.35	20.01	48.03	0.01
41005	Ouse at Gold Bridge	542750	121500	182.23	835	0.49	40.9	0.92	0.35	15.3	74.92	0.02

Number	Name	*IHDTM*	*NGR*	*AREA*	*SAAR*	*BFIHOST*	*SPRHOST*	*FARL*	*PROPWET*	*DPLBAR*	*DPSBAR*	*URBEXT_1990*
41006	Uck at Isfield	545900	118950	87.92	822	0.43	43.2	0.98	0.35	10.62	73.27	0.02
41028	Chess Stream at Chess Bridge	521850	117400	24.83	850	0.49	35.9	0.98	0.34	6.42	48.4	0.01
41801	Hollington Stream at Hollington	578800	110050	3.46	781	0.36	46.2	1	0.34	2.17	85.21	0.43
45002	Exe at Stoodleigh	294250	117650	420.74	1360	0.49	38	0.98	0.48	26.49	145.44	0
45004	Axe at Whitford	326250	95400	288.42	994	0.49	38.8	0.99	0.39	18.7	92.15	0.005
45011	Barle at Brushford	292700	125850	128.02	1585	0.44	42.8	0.99	0.54	21.81	139.27	0
46005	East Dart at Bellever	265750	77650	22.22	2096	0.36	47.5	1	0.46	6.22	96.98	0
52010	Brue at Lovington	359150	131800	139.13	867	0.52	36.4	0.99	0.37	13.46	72.51	0.007
53005	Midford Brook at Midford	376350	161150	147.41	965	0.62	29.1	0.99	0.36	13.76	81.94	0.03
53007	Frome(somerset) at Tellisford	380650	156250	262.05	965	0.56	29.8	0.96	0.36	20.5	61.77	0.01
53008	Avon at Great Somerford	396450	183200	305.11	804	0.62	28	0.98	0.34	18.39	29.17	0.008
54004	Sowe at Stoneleigh	433200	273250	263.23	667	0.5	35.8	0.98	0.3	16.99	28.39	0.13
54011	Salwarpe at Harford Mill	386850	261950	186.52	666	0.52	35.2	0.99	0.28	13.43	42.82	0.04
54019	Avon at Stareton	433150	271500	345.5	654	0.42	42.5	0.95	0.29	37.53	30.75	0.03
54034	Dowles Brook at Dowles	376650	276500	42.06	715	0.63	19.2	0.99	0.32	7.49	93.3	0.005
55013	Arrow at Titley Mill	332950	258500	125.66	962	0.55	34.3	0.99	0.49	14.4	132.58	0.003
55022	Trothy at Mitchel Troy	350150	211250	142.39	887	0.57	36.9	0.99	0.36	17.89	101.32	0.001
55026	Wye at Ddol Farm	297650	267450	172.2	1635	0.42	43.4	0.99	0.59	18.01	183.92	0.002
56003	Honddu at The Forge Brecon	305000	229850	62.46	1171	0.52	35.2	1	0.53	10.46	123.81	0
56005	Lwyd at Ponthir	332850	192400	98.33	1394	0.525	33.1	0.979	0.49	15.59	147.06	0.0783
56006	Usk at Trallong	294550	229650	194.23	1666	0.47	40.7	0.96	0.62	12.78	138.64	0.001
57004	Cynon at Abercynon	308050	195600	103.47	1772	0.42	40.1	0.98	0.53	15.18	145.76	0.03
57005	Taff at Pontypridd	308050	189650	451.88	1832	0.4	43.3	0.95	0.5	22.62	167.05	0.04
57006	Rhondda at Trehafod	305250	191000	102.61	2183	0.36	47.8	0.98	0.49	14.06	214.98	0.05
58003	Ewenny at Ewenny Priory	291550	178100	63.51	1321	0.55	29	1	0.52	8.19	76.4	0.03
58006	Mellte at Pontneddfechan	291350	208100	65.38	1981	0.32	51.3	0.97	0.62	10.44	134.91	0
60002	Cothi at Felin Mynachdy	250850	222500	298.7	1551	0.5	37.9	0.99	0.56	27.72	177.03	0
61001	Western Cleddau at Prendergast Mill	195250	217850	197.69	1276	0.56	32.6	0.99	0.44	15.65	69.42	0.001
61003	Gwaun at Cilrhedyn Bridge	200400	235000	31.2	1550	0.49	39.1	1	0.44	5.21	122.07	0
66011	Conwy at Cwm Llanerch	280300	358250	339.62	2041	0.36	48.9	0.98	0.7	16.42	173.11	0.001
68006	Dane at Hulme Walfield	384600	364250	149.07	1020	0.41	39.1	0.98	0.5	18.9	117.9	0.02
69013	Sinderland Brook at Partington	372700	390500	44.83	827	0.48	32.8	0.98	0.39	7.58	12.69	0.2

Number	Name	IHDTM	NGR	AREA	SAAR	BFIHOST	SPRHOST	FARL	PROPWET	DPLBAR	DPSBAR	URBEXT_1990
69027	Tame at Portwood	390450	391900	146.09	1212	0.36	42.6	0.92	0.54	26.46	124.05	0.1
70006	Tawd at Newburgh	346900	410850	28.33	946	0.6	23.2	1	0.51	6.42	34.08	0.11
72002	Wyre at St Michaels	346450	441050	272.6	1253	0.36	44.2	0.95	0.56	17.6	74.53	0.006
72006	Lune at Kirkby Lonsdale	361500	477950	509.98	1652	0.42	43	0.99	0.71	31.65	174.59	0.001
72818	New Mill Brook at Carvers Bridge	347900	438000	65.04	1076	0.39	39.7	0.99	0.51	9.47	29.42	0.01
73005	Kent at Sedgwick	350900	487550	212.28	1725	0.51	38.1	0.98	0.71	18.92	158.65	0.01
73008	Bela at Beetham	349600	480450	132.28	1290	0.53	32.5	0.96	0.68	13.43	89.32	0.003
74001	Duddon at Duddon Hall	319550	489550	86.02	2265	0.33	53.7	0.98	0.71	10.78	215.66	0
77002	Esk at Canonbie	339700	575250	495.32	1423	0.4	44.3	0.99	0.61	33	168.74	0.001
84008	Rotten Calder Water at Redlees	267950	660250	55.12	1217	0.31	42.2	0.99	0.58	12.85	53.81	0.06

Appendix F Results of flood event analysis

		Baseflow		Loss model	Routing model		
Catchment	No. events	*BL* (hr)	*BR* (-)	C_{max} (mm)	*Tp* (hr)	*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
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

Catchment	No. events	BL (hr)	BR (-)	C_{max} (mm)	Tp (hr)	Up (*)	Uk (-)
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
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 G Seasonal maximum rainfall

Introduction

The depth-duration-frequency (DDF) design rainfall model published as part of the FEH (Faulkner, 1999) enables users to make estimates of design floods at any location or for any catchment, as defined on the FEH CD-ROM, in the UK. The FEH DDF model was developed analysing annual maximum rainfall at different durations through an index flood method where a design estimate is obtained as the product between a scale parameter (the median of annual maximum rainfall for a given duration) and a dimensionless growth curve depending only on location and considered return period. The index rainfall was mapped through the combined use of multivariate linear regression and kriging. A large number of possible physical catchment descriptors were developed and tested as part of the study. Next, the dimensionless growth curves were modelled using the FORGEX method as detailed in Faulkner (1999).

To develop a set of DDF models based on seasonal maximum rainfall similar to the FEH DDF model based on annual maximum rainfall would clearly be a very time consuming and cumbersome procedure. Furthermore, the use of observed records with limited length might introduce enough sampling uncertainty in the estimated distributions to result in non-consistent results such as estimates of seasonal rainfall being larger than annual rainfall.

The objective of this appendix is to consider an alternative method for deriving estimates of seasonal design rainfall for a range of storm durations and to map the spatial distribution of seasonal maximum rainfall in England, Wales and Scotland. Seasonal correction factors are derived and used for obtaining estimates of seasonal maximum rainfall directly from estimates of annual maximum rainfall. The latter are readily available from the FEH CD-ROM.

Data material

Data series of seasonal and annual maximum 1-day rainfall depth were extracted from 172 recording raingauges and 523 long term daily rain gauges. The locations of the recording raingauges and the long term daily raingauges gauges are shown in Figure G.1 and G.2, respectively.

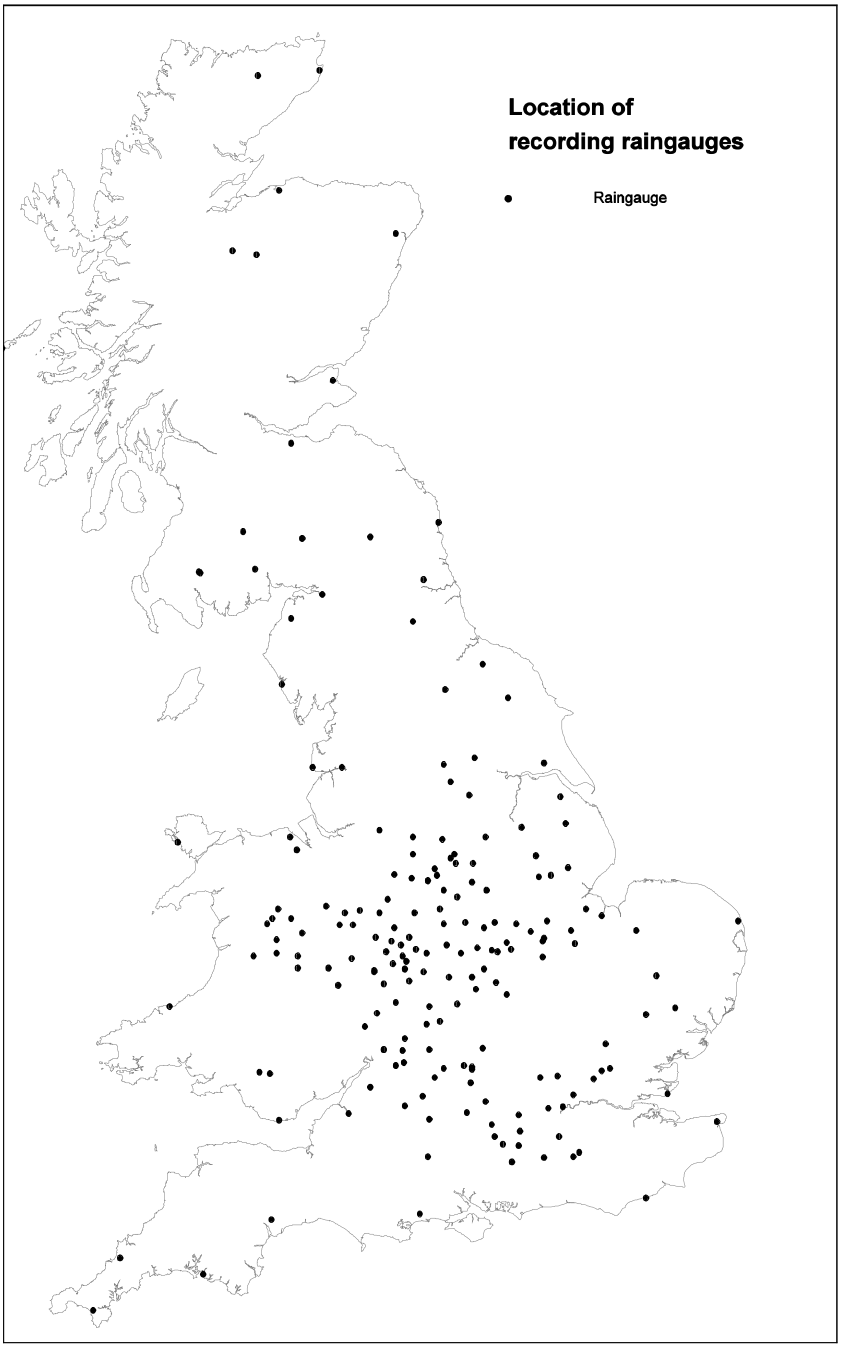


Figure G.1 Locations of the 172 recording raingauges

As seen from Figure G.1, the recording raingauges are mainly located in central England.

Figure G.2 Locations of the 523 long-term daily raingauges

The definition of the seasons adopted in this study corresponds to that of Dales and Reed (1989), i.e., summer and winter is defined May-October and November-April, respectively. The annual maximum data are based on a year from May to May the following year, which differs slightly from the calendar year adopted by Faulkner (1999) for deriving FEH design rainfall.

Methodology

In a design situation, a user of the present FSR/FEH Rainfall-Runoff method would obtain an estimate of the design storm depth directly from the FEH CD-ROM as explained in FEH Vol. 2 (Faulkner, 1999). This estimate is based on annual maximum series of rainfall depth. It is envisaged that for a design storm, the revitalised Rainfall-Runoff method will apply the design rainfall estimates obtained from the FEH CD-ROM but will produce an additional correction factor for estimation of the seasonal maximum rainfall. The seasonal and annual maximum rainfall will be related as

$$P_{d,i} = \lambda_{d,i} P_{d,A}\,, \quad i = \text{s,w}, \quad d = \text{1h, 2h, 6h , 1d} \tag{G.1}$$

where $P_{d,i}$ is the d-hour/day rainfall in the i'th season (summer or winter) for a specified return period, $P_{d,A}$ is the corresponding d-hour/day rainfall based on annual maximum rainfall and $\lambda_{d,i}$ is a correction factor depending on location, season, duration and considered return period.

To form estimates of $\lambda_{d,i}$ a Generalised Extreme Value (GEV) distribution was fitted to the extracted series of annual and seasonal maximum rainfall. Records of sub-daily rainfall were included if more than 10 years of maxima were available and for the longer daily records where more than 20 maxima were available. The parameters of the GEV distributions were estimated through the method of L-moments, using the sample median for estimation of the location parameter, as described by Robson and Reed (1999). For each gauging station, estimates of $\lambda_{d,i}$ were obtained as

$$\lambda_{d,i} = \frac{x_{d,i}(\boldsymbol{\Delta}_i)}{x_{d,A}(\boldsymbol{\Delta}_A)}\,, \qquad i = \text{s,w}, \quad d = \text{1h, 2h, 6h, 1d} \tag{G.2}$$

Where $x_{d,i}$ and $x_{d,A}$ are the T-year events for the i'th season and the annual series, respectively, and $\Delta = (\xi, \beta, \kappa)^T$ is a vector of the GEV parameters. In theory, $\lambda_{d,i}$ should not be able to exceed one, which is when all observed seasonal maxima have occurred in the same season. However, due to sampling uncertainty the seasonal maxima can in certain cases exceed the annual maxima at high return periods.

Furthermore, predictions of the T-year events at high return periods will often be extrapolations beyond the observed samples. In practice, the longest records extend approximately 100 years back in time for the daily records and much less in the case of the sub-daily records. Therefore, the results at high return periods are associated with a higher sampling uncertainty than corresponding results at low return periods. To avoid problems associated with excessive extrapolation it was decided only to consider the seasonal correction factors derived for a return period of five years. This has the added benefit of allowing a direct comparison with the results reported in FSR Vol 2, Table 3.9 (NERC, 1975).

Regionalised seasonal correction coefficients

The regionalisation of the seasonal correction factors has been obtained by linking them to Standard Average Annual Rainfall (*SAAR*) as extracted from the FEH CD-ROM at the 1km grid point closest to the considered rain gauge. The seasonal correction factors for different durations and for both summer and winter are plotted against *SAAR* for selected return periods in Figure G.3 and Figure G.4. For the summer season, the correction factors are generally close to one in areas of low *SAAR* and gradually decreasing as *SAAR* increases. For the winter season, the correction factors are relatively low at gauges located in areas of low *SAAR* and then converging towards one for increasing *SAAR* values. For both seasons a significant variability is evident, but the pattern outlined above is observed for all considered durations. The results correspond well to values of seasonal variation of maximum rainfall reported in the Flood Studies Report Vol. II Table 3.9 (NERC, 1975) for the five-year return period.

Functional relationships between the seasonal correction factors and *SAAR* were developed. The relationships were selected to be able to produce realistic estimates of the seasonal correction factors for all values of *SAAR* encountered in the UK and, at the same time, to have a limited number of parameters to facilitate user friendliness.

The winter seasonal correction factor is modelled using an exponential type relationship given as

$$\lambda_w = \left[1 - \exp\left(-\varphi SAAR\right)\right]^{\psi} \qquad \text{(G.3)}$$

where the two model parameters are estimated using least square techniques. Plots of observed and modelled winter season correction factors are shown in Figure G.3. The plots include the relationship in Eq. (G.3) with both parameters estimated from the data and with a fixed value of ψ=1 and only φ estimated from the data. As the two parameters (ψ and φ) version of Eq. (G.3) was found to align better with the results from the FSR study, it was recommended for practical use.

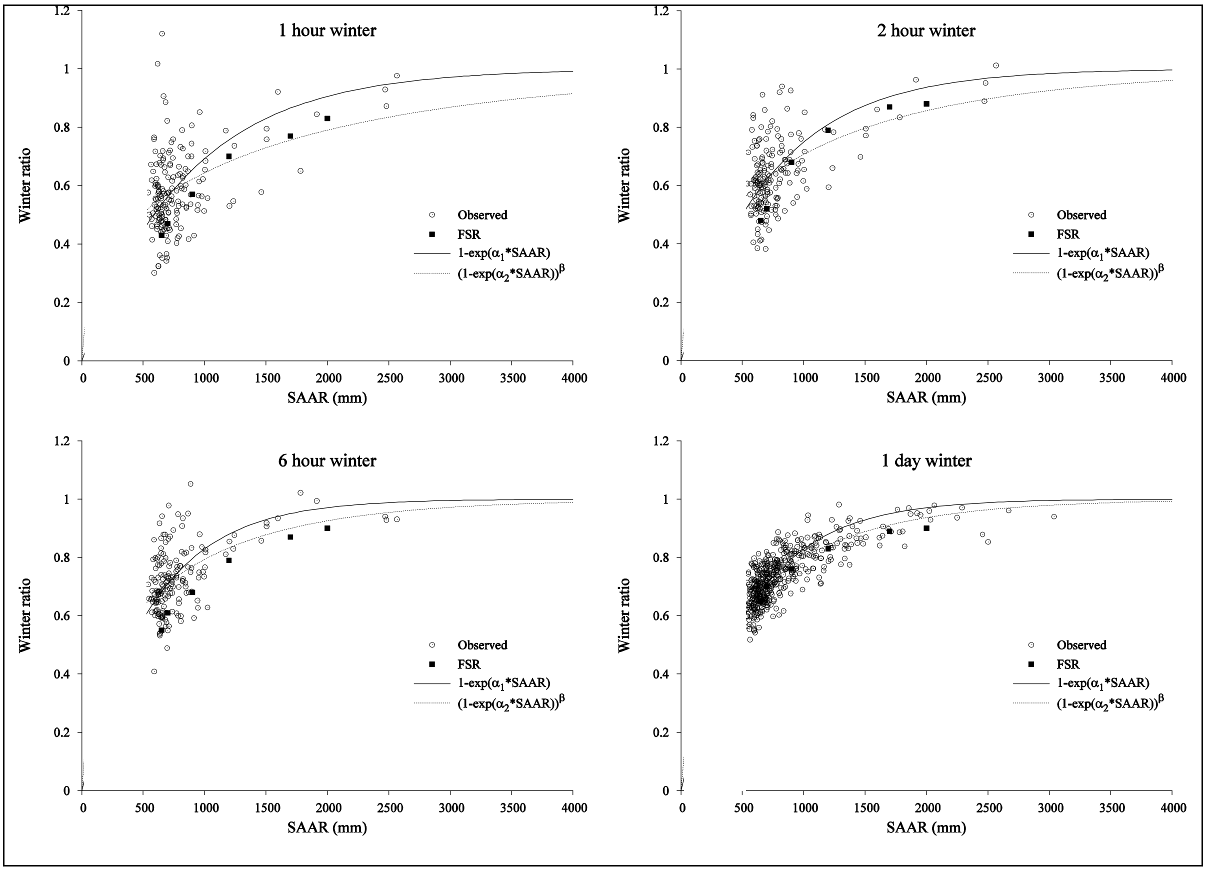


Figure G.3 Observed and modelled winter season correction factors.

For the summer season, the relationship between the correction factor and *SAAR* was modelled using a simple linear relationship

$$\lambda_d = \alpha \, SAAR + \beta \qquad \text{(G.4)}$$

with the constraint that for *SAAR* equal to 500 mm, the correction factor should equal one. This constraint insures that in practice no estimates larger than one can be obtained as no *SAAR* value lower than 500 mm exists anywhere on the FEH CD-ROM. Again, the free parameter (intercept) was estimated using the least square technique. Plots of observed and modelled summer season correction factors for each of the considered durations are shown in Figure G.4.

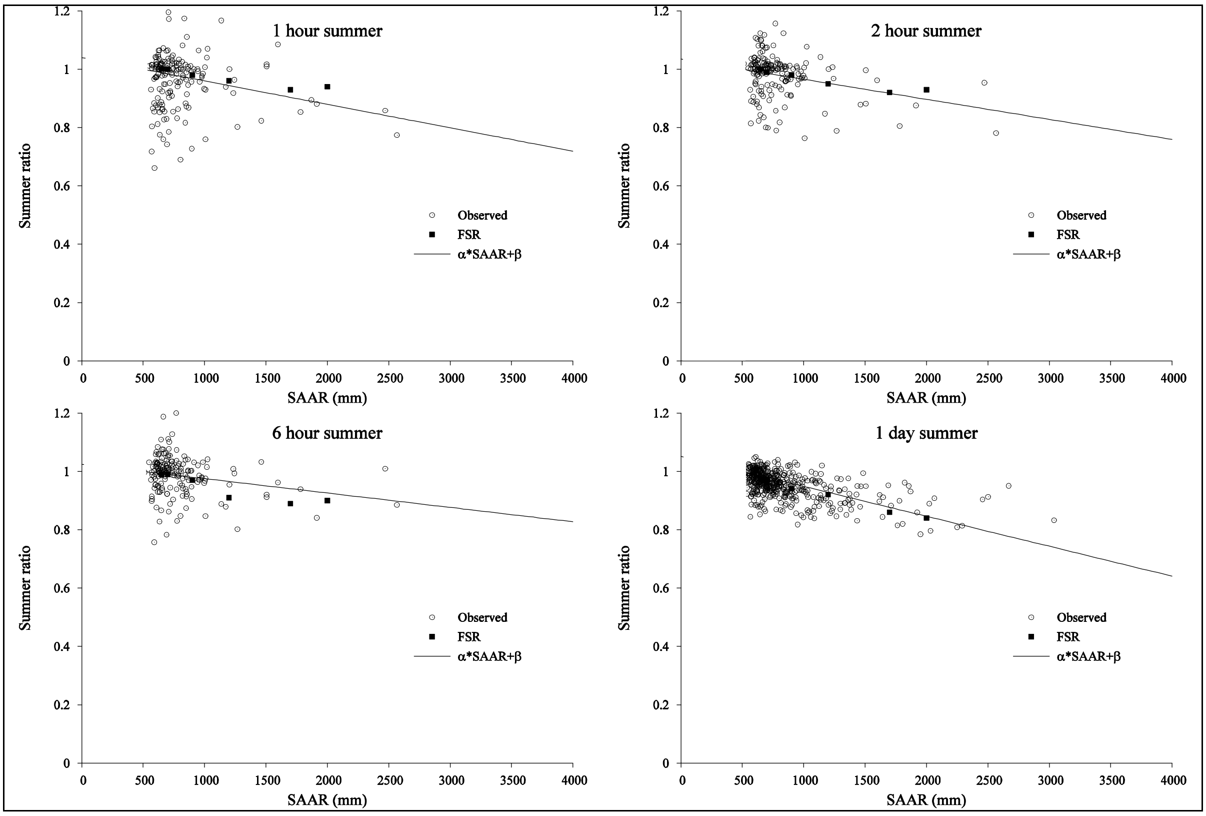


Figure G.4 Observed and modelled summer season correction factors.

The parameters obtain for both seasons and for each of the considered durations are shown in Table G.1 below.

Table G.1 Parameter values for relationships between *SAAR* and seasonal corrections factors for different durations.

	Summer		Winter		
Duration	α	β	φ (ψ=1)	φ	ψ
1 hour	-8.03 10-5	1.04	0.0012	0.0004	0.4000
2 hour	6.87 10-5	1.03	0.0014	0.0006	0.4454
6 hour	4.93 10-5	1.02	0.0018	0.0009	0.4672
1 day	10.26 10-5	1.05	0.0018	0.0011	0.5333

To obtain parameters for durations not included in Table G.1, simple interpolation between the values can be applied.

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Revitalisation of the FSR/FEH rainfall-runoff model

Technical Summary: FD1913

Joint Defra / EA Flood and Coastal Erosion Risk Management R&D programme

Background to R&D project

The FSR/FEH rainfall-runoff method is a widely used tool for design flood estimation in the UK. The method was first documented in the Flood Studies Report (FSR) in 1975, and since then numerous studies have updated and improved the method. The latest revision was the technical restatement of the method published in Volume 4 of the Flood Estimation Handbook (FEH) in 1999. Despite these improvements, the basic model structure and the design estimation package have remained unchanged since the first FSR version. The widespread use of the method has prompted valuable feedback from the user community, including critical observations about existing procedures and areas in need of improvement. The aim of this project was to make improvements to the key components of the FSR/FEH rainfall-runoff method taking advantage of new data, updated analytical techniques and recent advances in computation.

Results of R&D project

The outcome of the project is a revitalised and improved method for event-based flood modelling in the UK. The modifications include, improved rainfall-runoff modelling techniques and a method for generating design flood events with added emphasis on quantifying the underlying physical flood-generating mechanisms. To improve confidence in the performance of the method, especially at high return periods, extra hydrological data from recent large flood events were collected from catchments throughout the UK and added to the existing flood event archive.

A key part of the project was the development of a new physically-based conceptual rainfall-runoff model, the Revitalised Flood Hydrograph (ReFH) model, for the modelling of flood events. The ReFH model is based on robust hydrological modelling techniques and is considered to be a significant improvement over the existing FSR/FEH model. The ReFH model allows a more direct and transparent quantification of flood-generating mechanisms, and the concept of seasonal variation in soil moisture content and design rainfall is introduced. Based on the results obtained from applying the ReFH model to observed flood events from 101 catchments located throughout the UK, a set of equations was developed allowing users to estimate the model parameters for any catchment in the UK larger than 0.5 km^2.

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Based on the ReFH model, a design method has been developed which allows for the generation of design flood hydrographs through the specification of initial soil moisture content, design rainfall and required return period. Both soil moisture and rainfall are specified on a seasonal basis depending on the degree of urbanisation of the catchment under consideration (summer conditions for urbanised catchments and winter conditions for rural catchments). Validation of the design method confirmed that the method for most catchments is within ±10% of the peak flow estimates obtained from a statistical analysis of annual maximum peak flow data on the same catchments.

R&D Outputs and their Use

The Revitalised rainfall-runoff method developed in this study is intended to replace the existing FSR/FEH rainfall-runoff method as detailed in the Flood Estimation Handbook (FEH) Vol. 4, enabling the estimation of design hydrographs for use in hydraulic engineering and flood management. It is anticipated that users of the existing FSR/FEH method, including the Environment Agency, local authorities and consulting engineers, will adopt the ReFH method.

To support the dissemination of the results, a user-friendly spreadsheet implementation of the design method has been developed and will be made available to users via the FEH homepage free of charge. In addition, the Environment Agency has funded a follow-on project to develop a more comprehensive software package, which will allow users to analyse data from observed flood events as well as to conduct reservoir routing studies.

The benefits to Defra/Environment Agency are a framework for event-based flood modelling founded on a more physical consideration of the catchment flood hydrology, and an improved design method. The method will enable more detailed studies of flood hydrology and the underlying flood-generating mechanisms, thereby enhancing flood management on a national basis.

This R&D Technical Summary relates to R&D Project FD1913 and the following R&D output:

- **R&D Technical Report FD1913/TR – Revitalisation of the FSR/FEH Rainfall-Runoff model.** Published January 2006.

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The above outputs may be downloaded from the Defra/EA Joint R&D FCERM Programme website (www.defra.gov.uk/environ/fcd/research). Copies are also available via the Environment Agency's science publications catalogue (http://publications.environment-agency.gov.uk/epages/eapublications.storefront) on a print-on-demand basis.

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