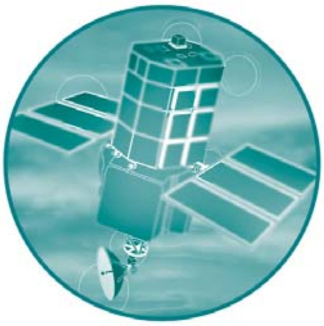
Joint Defra / EA Flood and Coastal Erosion Risk Management R&D Programme



Dissemination of the revitalised FSR/FEH rainfall-runoff method

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Department for Environment Food and Rural Affairs

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Executive Summary

Background:

Following the successful completion of the joint Defra / Environment Agency funded R & D project FD1913 Revitalisation of the FSR/FEH rainfall-runoff method, it was subsequently decided that additional effort was needed to effectively disseminate the new method to the wider hydrological community in the UK and beyond. Thus, the Environment Agency initiated the current project (SC040029) Dissemination of the revitalised FEH rainfall-runoff method.

Aims

The objective of this project is to facilitate the dissemination of the revitalised FSR/FEH rainfall-runoff method through the development of three individual products

i) a free EXCEL spreadsheet implementation of the revitalised FSR/FEH design method,
ii) a comprehensive software package supporting all modelling aspects of the revitalised FSR/FEH rainfall-runoff method, and
iii) A supplementary report to the existing five-volume Flood Estimation Handbook (FEH)

Results:

The ReFH design spreadsheet was made available for downloading free of charge on the 19 January 2006 from a dedicated web-page hosted by the Centre for Ecology & Hydrology. Within two months of release, in excess of 250 individuals from public, private and academic institutions had downloaded a copy of the spreadsheet.

A comprehensive ReFH Flood Modelling Software package supports all aspects of the revitalised FSR/FEH rainfall-runoff method, including import, storage and retrieval of observed hydrometric data, estimation of parameters for the Revitalised Flood Hydrograph (ReFH) model through analysis of observed flood events, simulation of both observed and design flood events and, finally, reservoir routing functionalities. The software has been developed for the Windows platform and is accompanied by a comprehensive user manual.

An application-oriented description of the revitalised FSR/FEH rainfall-runoff method is provided in a report supplementing the existing five-volume Flood Estimation Handbook. The report consists of six chapters providing a description of the ReFH model, methods for estimating the ReFH model parameters, a description of the ReFH design method, practical user guidance and two examples where the method has been applied to simulate a design hydrograph and to model an observed event, respectively.

Conclusions:

It is believed that the three products developed in this study will further facilitate the dissemination of the revitalised FSR/FEH rainfall-runoff method to the hydrological community in the UK. However, considering the success of the free spreadsheet, it is important to emphasise the need to adhere to best practice in flood risk analysis, i.e. to include and analyse local observed flood data where possible. This analysis cannot be carried out in the spreadsheet and access to the comprehensive software package (or another similar software implementation of the method) is necessary.

Contents

1. Introduction

1.1 Background

This report represents the final outcome of the Environment Agency-led R & D project SC040029 Dissemination of the revitalised FEH rainfall-runoff method, funded by the Joint Defra/Environment Agency Flood and Coastal Management R & D programme. The objective of the current project is to disseminate the revitalised FSR/FEH rainfall-runoff method to the user community via two separate software implementations of the method, a website, and an FEH Supplementary Report.

In 2002, the Centre for Ecology & Hydrology (CEH) in Wallingford was commissioned by the Joint Defra/Environment Agency Flood and Coastal Management R & D programme to undertake a revision of the existing FSR/FEH rainfall-runoff method (project FD1913) and to address the concerns raised by the user community. The outcome was the revitalised FSR/FEH rainfall-runoff method as described by Kjeldsen *et al.* (2006). In the current report only a brief summary of the method is presented. For a full description of the method and the associated procedures please refer to Kjeldsen *et al.* (2006) or the FEH Supplementary Report published as part of this project (Kjeldsen, 2006).

1.2 The revitalised FSR/FEH rainfall runoff method

1.2.1 The FSR/FEH rainfall-runoff method

The FSR/FEH rainfall-runoff method is a UK-based tool for design flood estimation often used alongside statistical methods for flood frequency analysis where estimates of complete flood hydrographs and flood volumes are required. The method was first documented in the Flood Studies Report (FSR) in 1975 (NERC, 1975) and further refined in subsequent Flood Studies Supplementary Reports published by the Institute of Hydrology. Volume 4 of the Flood Estimation Handbook (FEH) (Houghton-Carr, 1999) presented a comprehensive technical restatement of the method, but, despite some improvements, the basic model structure and the design estimation procedure remained largely unchanged from the first FSR version. The widespread use of the method has prompted valuable feedback from both the user communities, both practical and academic. The feedback included critical observations concerning specific procedures and areas in need of improvement.

1.2.2 The revitalised flood hydrograph (ReFH) rainfall-runoff model

At the core of the revitalised FSR/FEH rainfall runoff method is the revitalised flood hydrograph (ReFH) rainfall-runoff model, developed to constitute a radical improvement of the hydrological modelling aspects of the method but, at the same time, to resemble the existing FSR/FEH model as closely as possible to facilitate user acceptance and uptake of the method. As with the existing FSR/FEH model, the ReFH model consists of three main model components: a loss model, a routing model and a baseflow model. The interactions between the three model components are illustrated in Figure 1.1, together with the required input variables (rainfall, initial soil moisture and initial baseflow) and model parameters.

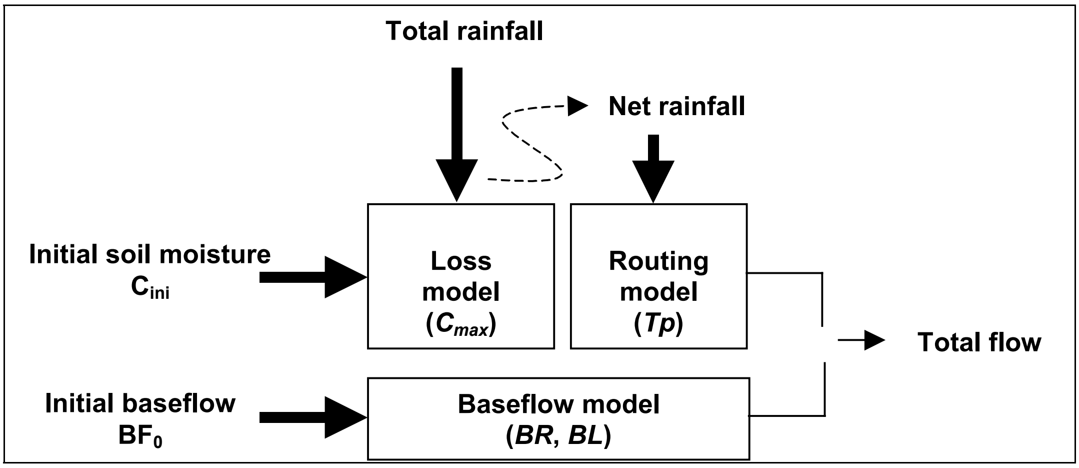

Figure 1.1 Schematic representation of the ReFH model

When simulating a flood event the role of the loss model is to estimate the percentage of total rainfall which is turned into direct runoff. Next, the direct runoff is routed to the catchment outlet using standard unit hydrograph convolution technique as specified by the routing model. Finally, the baseflow component is added to the direct runoff to obtain total runoff. Details of the three model components can be found in Kjeldsen *et al.* (2006) or in the FEH supplementary report published as part of this study (Kjeldsen, 2006); only a short summary is given here.

1.2.3 Loss model

The ReFH loss model is based on the Probability Distributed Model (PDM) developed by Moore (1985) and widely used in the UK for a variety of practical hydrological applications such as flood forecasting (Moore, 1999) and continuous simulation modelling (Faulkner and Wass, 2005). To derive the percentage runoff in the ReFH model, consider a rainfall pulse P_t falling on a catchment with soil moisture content C_t, then the excess amount of rainfall converted into direct runoff, q_t, can be estimated as

$$\frac{q_t}{P_t} = \frac{C_{t-1}}{C_{\max}} + \frac{P_t}{2C_{\max}}, \quad \text{for } t = 1, 2, 3, \ldots \qquad \text{and} \quad C_{t+1} = C_t + P_t \qquad (1.1)$$

where q_t/P_t is the ratio of rainfall transformed into runoff (percentage runoff) and C_{max} is the maximum soil moisture capacity within the selected catchment. Equation 1.1 is evaluated sequentially during the storm and if the total capacity of the soil is exceeded the percentage runoff will equal 100%. To begin the sequential calculation of losses, the model requires specification of the soil moisture content C_{ini} at the onset of the flood event, i.e. at time t = 0.

1.2.4 Routing model

In the ReFH model, routing of net rainfall (direct runoff) to the catchment outlet is based on the unit hydrograph concept. The original FSR/FEH model adopted a standard triangular-shaped instantaneous unit hydrograph (IUH) scaled to each catchment using catchment area and the time to peak (*Tp*) parameter. Based on analysis of observed events using the ReFH model, a kinked triangle has been adopted as the standard IUH. The shape of the IUHs used in the ReFH model and the FSR/FEH model, respectively, are shown in Figure 1.2.

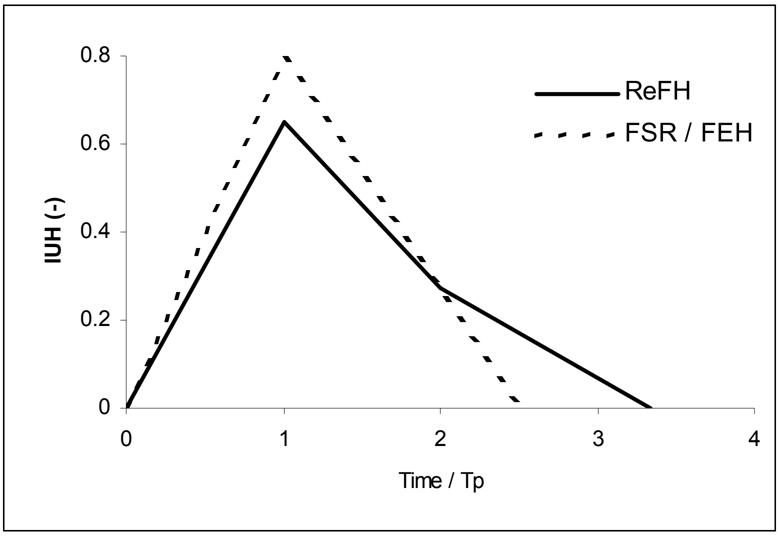

Figure 1.2 Comparison of the FSR/FEH and the ReFH standard shaped instantaneous unit hydrographs

The IUH is converted to a unit hydrograph for the required time step Δt by using the standard S-curve method as described in most hydrological text books.

1.2.5 Baseflow model

A new baseflow model has been developed for implementation in ReFH based on a linear reservoir concept with its characteristic recession defined by an exponential decay controlled by the baseflow lag (*BL*). The baseflow model in FSR/FEH was a constant value, independent of direct runoff. The baseflow model in ReFH, however, works on the assumption that the input to the baseflow reservoir is related to the rate of the surface runoff where recharge is *BR* times the surface runoff. The model can be developed as a recurrence formula, and links baseflow, z_t, to surface runoff as

$$z_t = k_1 q_{t-1} + k_2 q_t + k_3 z_{t-1} \qquad \text{for t = 1, 2, 3,} \qquad (1.2)$$

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* (not shown here). Further details can be found in Kjeldsen (2006) and Kjeldsen *et al.* (2006). The actual model parameters are the baseflow recharge, *BR*, the baseflow lag, *BL*, and the initial baseflow, $z_0 = BF_0$, i.e. flow in the river just before the onset of the flood event.

1.2.6 Design method

The revitalised FSR/FEH rainfall-runoff method has been developed to allow design flood hydrographs to be generated for any catchment where the ReFH model parameters can be estimated. It is important to distinguish between the simulation of an observed event and the estimation of a design flood hydrograph. The latter is based on a design model constructed to produce the hydrograph of a specified return period when the input variables have been specified accordingly.

The design model is based on the ReFH model as illustrated in Figure 1.1, but requires probabilistic values of the input to be specified, i.e. a design hyetograph (depth-duration-frequency), initial soil moisture content (C_{ini}) and initial baseflow (BF_0). The design method was developed by forcing the peak flow of a flood event generated using the T-year rainfall to align with the corresponding T-year peak flow value derived from a statistical analysis. In addition, the revitalised FSR/FEH rainfall-runoff method developed seasonal input values for initial soil moisture and design rainfall.

A comprehensive description of the revitalised FSR/FEH rainfall-runoff method for design flood estimation, including description of how the method was developed, quantification of the flood generating mechanisms and examples of application is given by Kjeldsen (2006). A comparison between the FEH design method and the revitalised design method is shown in Figure 1.3 below.

	ReFH design model	FEH design model
Return period:	$T_{rain} = T_{flood}$	$T_{rain} \neq T_{flood}$
Seasonality:	Rainfall profile and depth, soil moisture and baseflow	Rainfall profile
Initial soil:	C_{ini} (SAAR, BFIHOST)	CWI (SAAR)
Rainfall:	FEH DDF model×season	FEH DDF model

Figure 1.3 Comparison between the FSR/FEH and the revitalised FSR/FEH rainfall-runoff method for design flood estimation

The comparison indicates that the revitalised FSR/FEH rainfall-runoff method constitutes a move towards a more physically based framework where seasonality in the flood generating mechanisms (rainfall and initial soil moisture) is more easily adopted than in the original FSR/FEH framework.

1.3 Dissemination strategy

The original FSR/FEH rainfall-runoff method was developed in the early 1970s before desktop computing facilities were widely available. Thus, the method was designed with the intention that the calculations could be done manually within a reasonable time. As part of the FSR (I.6.8.6), a listing of FORTAN code for deriving design flood hydrographs using the FSR method, including deriving rainfall profiles and performing the unit hydrograph convolution, was made available for users.

With the advent of personal computers, software packages were made available to the user community to facilitate the use of the method, especially Micro-FSR (IH, 1991), Isis (Wallingford Software, 2005) and Mike 11 (DHI, 2005) which are widely distributed and used in the UK.

Because of the widespread use of the FSR/FEH method, it is likely that other organizations have produced more in-house implementations not commonly available. In addition, the adoption of the method in other related areas of civil engineering, such as drainage engineering, has prompted the software implementations of the method or variants of the method in other software packages such as Micro Drainage (Micro Drainage Ltd) and InfoWorks (Wallingford Software Ltd).

To ensure a unified uptake of the revitalised FSR/FEH rainfall-runoff method, the Environment Agency commissioned the Centre for Ecology & Hydrology to produce a range of user-friendly tools supporting the dissemination of the method. Firstly, a user-friendly EXCEL spreadsheet implementation of the design method which has been made available unsupported but free of charge from the CEH website. Secondly, a more comprehensive ReFH Flood Modelling software package has been developed to enable users to estimate ReFH parameters through analysis of observed flood events and to conduct reservoir flood studies. Finally, a supplementary report to the existing five-volume FEH providing a user-friendly presentation of the method is being published. The structure of this report documents each of the three outputs in the following three chapters.

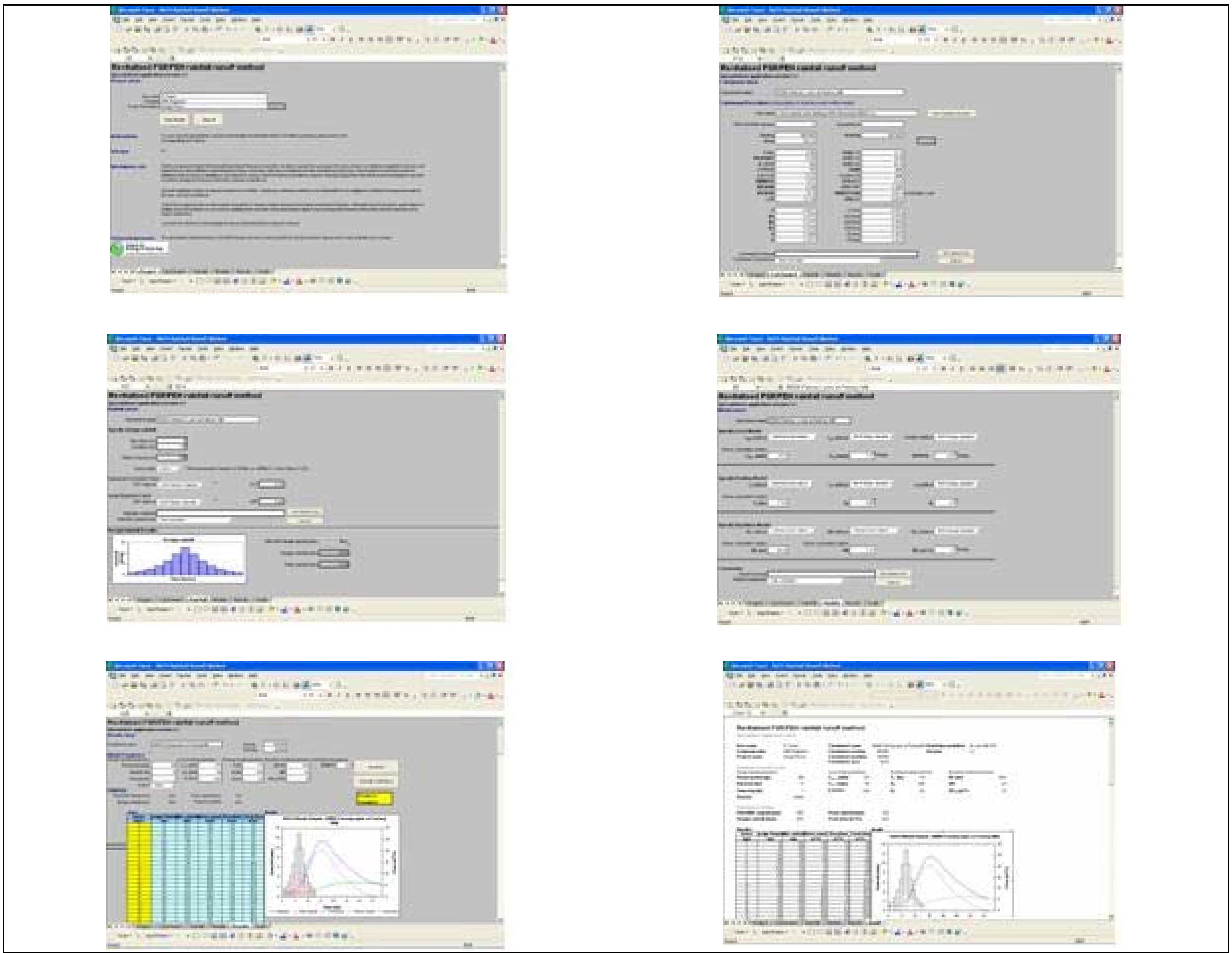

Figure 2.1 Screenshots of the six sheets in the ReFH design spreadsheet

Within the first 8 weeks from release into the public domain on the 19 January 2006, more than 250 downloads of the spreadsheet from both public and private institutions have been registered.

In Table 2.1 below is a snapshot of the comments made by people downloading the software, i.e. comments made before they have actually used the software.

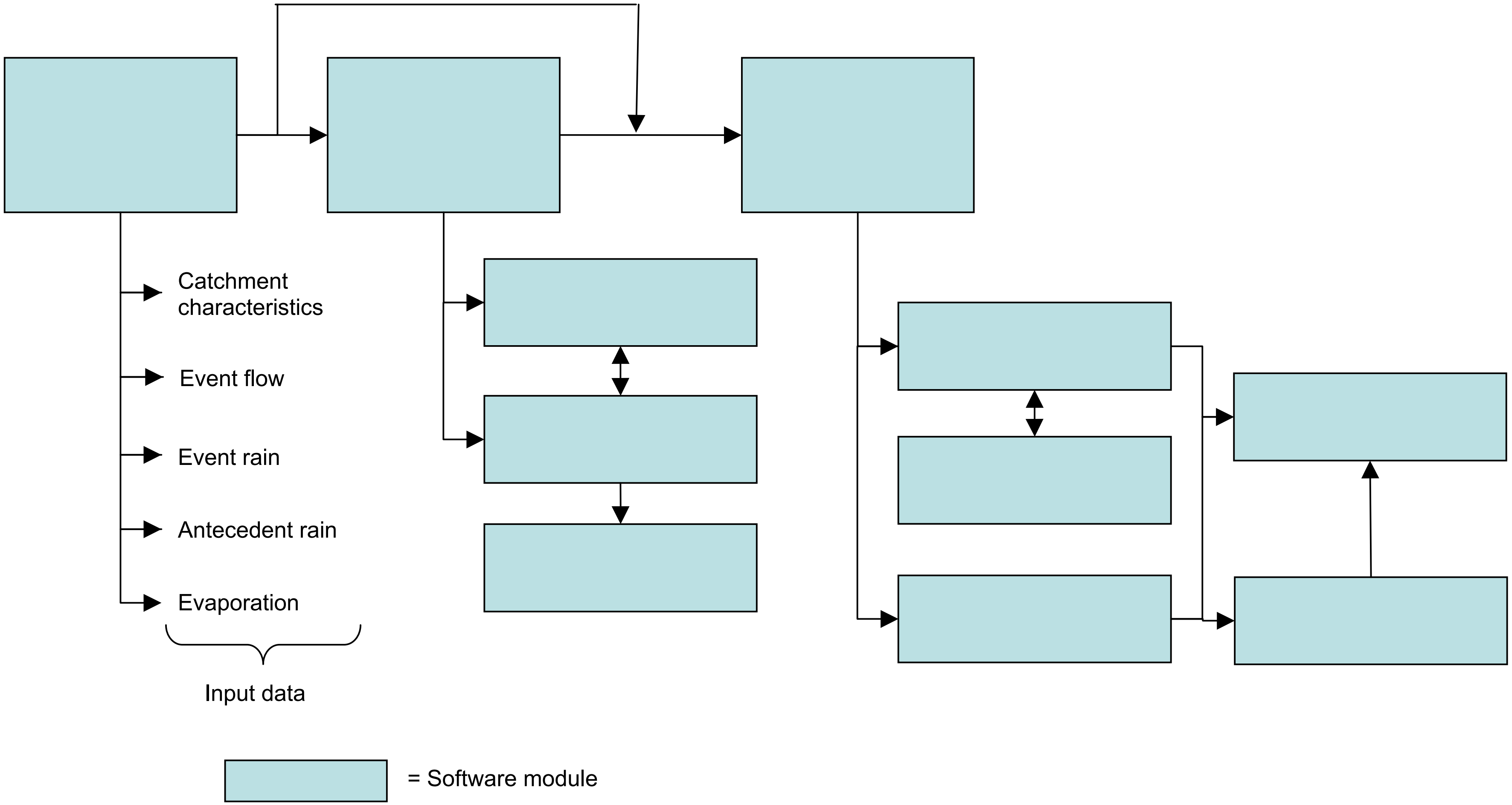

Figure 3.1 Schematic representation of the ReFH Flood Modelling software and the required input data

Secondly, the loss model and routing model parameters (C_{max} and Tp) are estimated jointly through an optimisation procedure seeking to minimise the difference between simulated and observed runoff considering all selected flood events. As part of the optimisation, it is also necessary to estimate the development of antecedent soil moisture content in order to obtain an estimate of the initial soil moisture content (C_{ini}) at the start of each flood event being considered.

From the initial *ReFH model parameter estimation* screen, shown in Figure 3.3, the user has access to a functionality defining the procedure for modelling the antecedent soil moisture for each individual flood event as well as the actual ReFH model parameter estimation procedures.

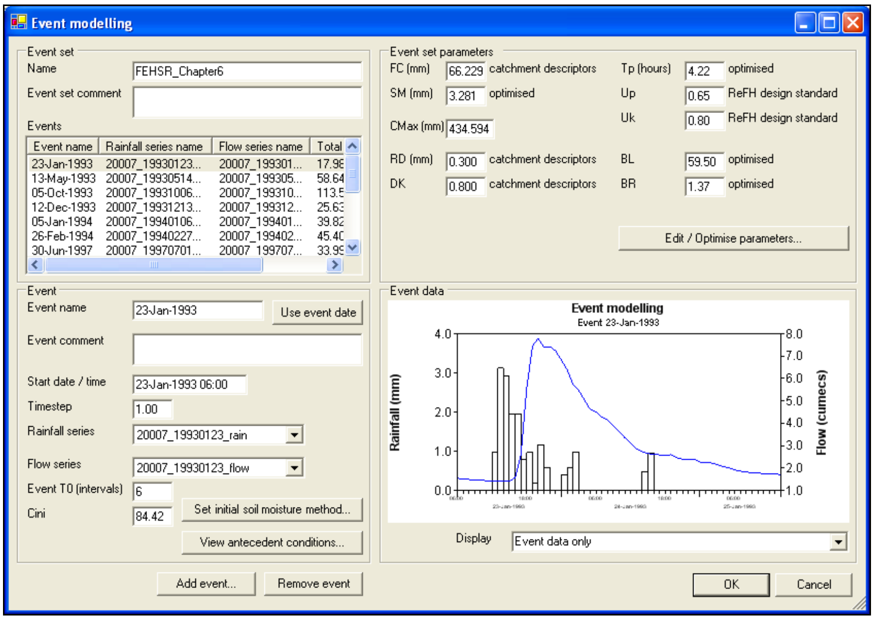

Figure 3.3 ReFH model parameter estimation start screen

In the following, each of the three modules: *Antecedent soil moisture modelling*, *baseflow parameter estimation* and *Optimise ReFH model parameters* are described in more details.

Antecedent soil moisture modelling

The initial soil moisture content (C_{ini}) for each flood event can be obtained simply as a fixed value (or fraction of C_{max}) or through hydrological modelling of the soil moisture content for a period of up to two years prior to the start of the flood event using daily average catchment rainfall and evaporation as described by Kjeldsen (2006). The screen where the user chooses how to estimate C_{ini} and the necessary setup for the modelling option are shown in Figure 3.4.

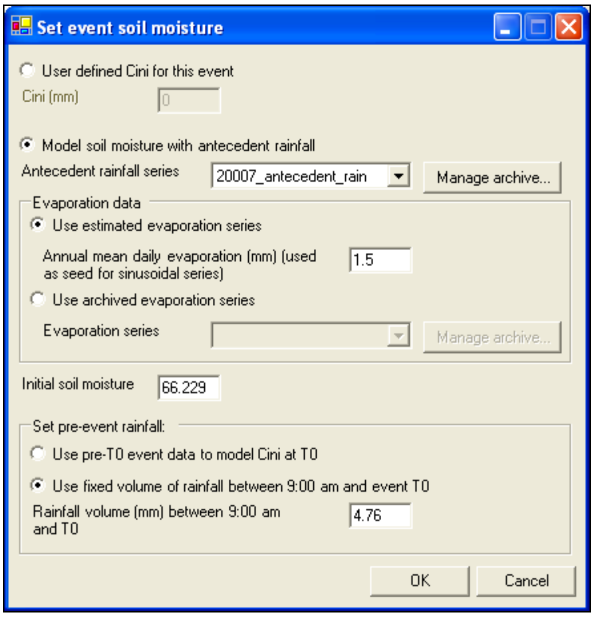

Figure 3.4 Options and setup for modelling of initial soil moisture content (C_{ini})

Examples of time series of the driving rainfall and evaporation are shown in Figure 3.5 plotted together with the resulting soil moisture content.

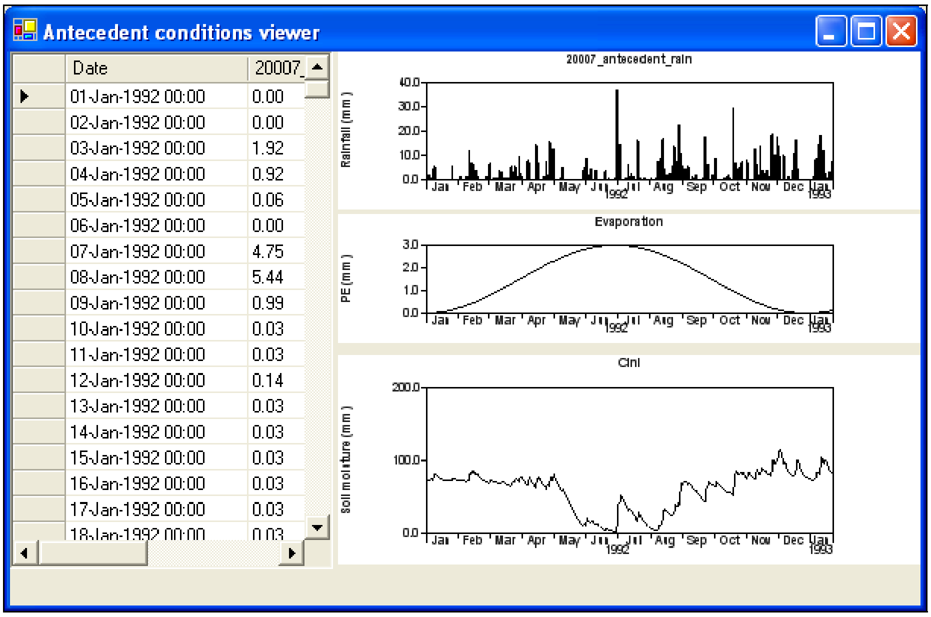

Figure 3.5 Daily average rainfall, evaporation and the resulting soil moisture content

Good estimates of C_{ini} are important when modelling the actual flood events as the soil moisture content plays a significant role in determining the percentage runoff. A rainfall event imposed on a catchment that is initially dry will result in a smaller percentage runoff than a similar rainfall event imposed on a wet catchment.

Optimise ReFH model parameters

The main screen for controlling the estimation of the ReFH model parameters is shown in Figure 3.6. For each parameter, the user is given a choice of estimation procedure. Each parameter can be estimated either as (i) a user-defined value, (ii) using catchment descriptors or (iii) through a parameter optimisation procedure. For some parameters, a fourth option for using ReFH design standard values is available and should preferably be chosen where possible. Having chosen to estimate a particular parameter through optimisation, it is necessary to define an upper and lower limit of the search interval as well as an initial value. Details of the optimisation procedure are described by Kjeldsen (2006).

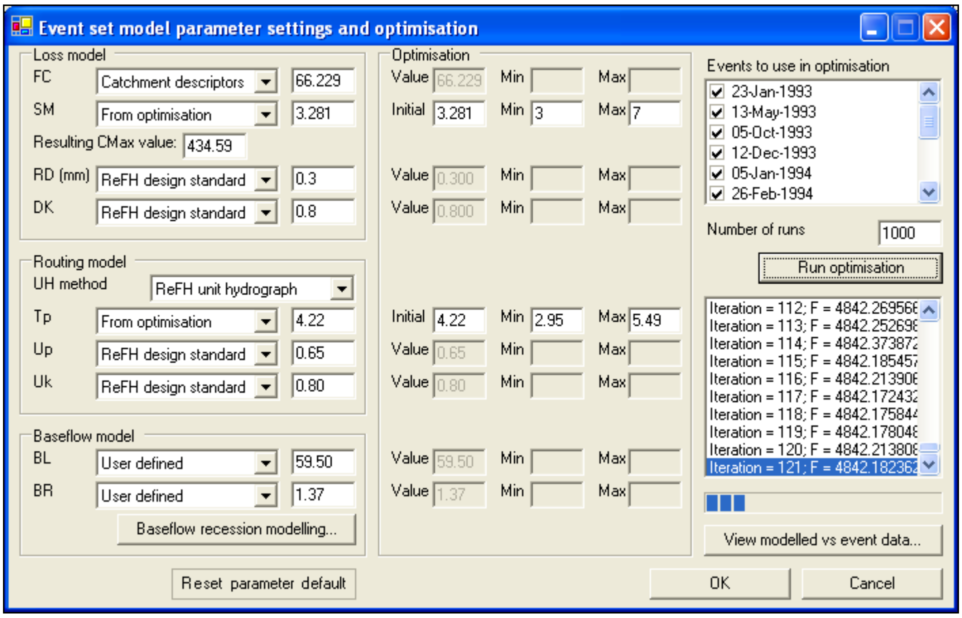

Figure 3.6 ReFH model parameter estimation functionality

To carry out the optimisation, a version of the hill-climbing multivariate optimisation routine (Rosenbrock, 1960), has been implemented in the software. The optimal solution is defined in terms of the mean square error (MSE) defined as the mean squared difference between observed and simulated runoff added up over all considered flood events. In principle, there is no limit to the number of model parameters that can be included. However, Kjeldsen *et al.* (2006) found that, in practice, the search for an optimal parameter set should be limited to two parameters, C_{max} and *Tp*, controlling the loss and routing models, respectively. For each optimisation run, the software has to re-estimate the initial soil moisture content (C_{ini}) as the maximum soil depth (C_{max}) is likely to have changed, hence the link between the modelling of the antecedent soil moisture modelling and the ReFH model parameter estimation in Figure 3.1.

The two baseflow parameters (*BL* and *BR*) should ideally be estimated through explicit modelling of the recession part of the observed hydrographs as described below.

Baseflow parameter estimation

The baseflow parameter estimation functionality is activated from within the *ReFH model parameter optimisation* menu, but has to be considered before estimating the remaining two model parameters C_{max} and *Tp*. An example of the functionality is shown in Figure 3.7.

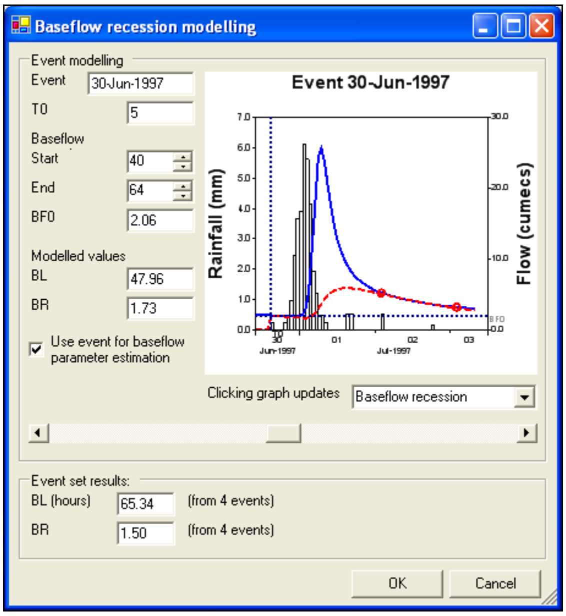

Figure 3.7 Baseflow parameter estimation module

For each event, two points on the recession have to be selected, defining end-of-direct-runoff and end-of-recession. Combined with an estimate of initial baseflow, the software will estimate the two baseflow parameters *BL* and *BR* as outlined by Kjeldsen (2006) for the particular event under consideration. For each observed event it has to be decided if the recession is considered sufficiently long for enabling a reliable estimate of the baseflow parameters. The final estimates of catchment values of the parameters are derived as an average of the estimates from the selected events.

3.2.3 Event modelling

Having obtained a fully calibrated ReFH model for a specific catchment, the next step is to simulate the catchment response to a particular rainfall-event combined with a specific value of the initial soil moisture content (C_{ini}) and initial baseflow (BF_0). The software enables the simulation of the catchment response to both observed rainfall events and design rainfall events. The two options are shown in Figure 3.8.

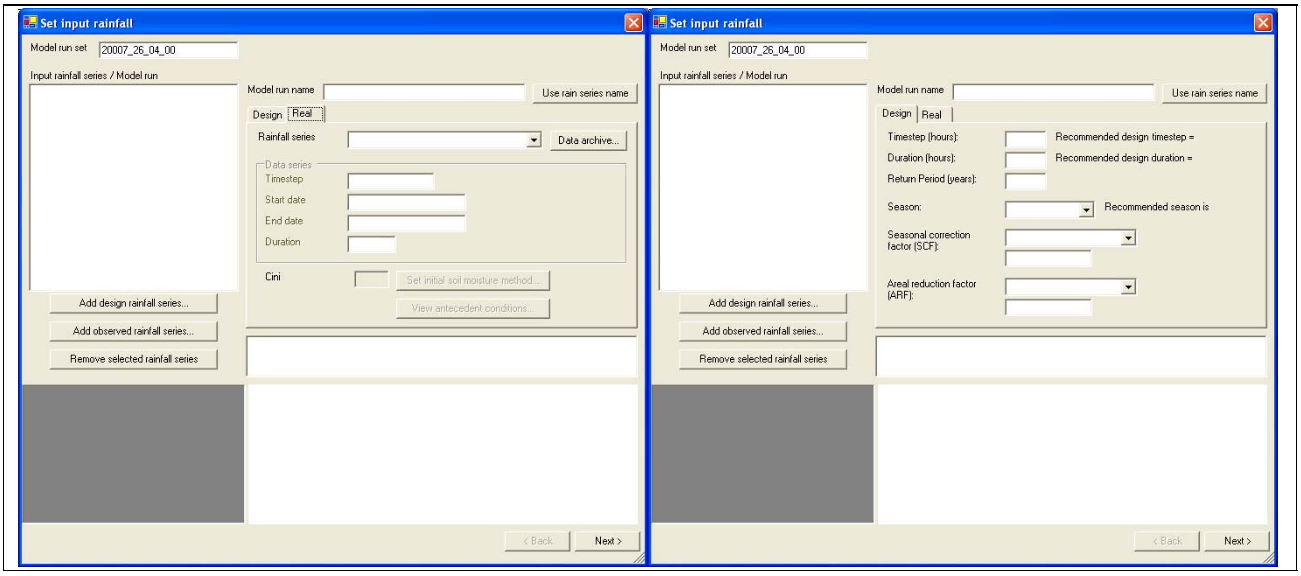

Figure 3.8 Modelling of an observed or a design flood event

Modelling of an observed event requires specification of a rainfall series available on the database as well as specification of the initial soil moisture content (C_{ini}) and the initial baseflow value (BF_0) for the particular event under consideration. The options for specification of C_{ini} are similar to those described above as part of the ReFH model parameter estimation method.

Simulation of a design event requires a design rainfall event (depth-duration-frequency) to be specified as well as design values of C_{ini} and BF_0. The procedure for simulating a design flood event is described in detail by Kjeldsen (2006) and is similar to the procedure implemented in the free EXCEL spreadsheet described in Section 2 of this report.

3.2.4 Reservoir routing

Within the ReFH software, the reservoir routing option has two main functionalities. First, it allows for a simple routing of a flood hydrograph through a reservoir and modelling the resulting outflow hydrograph and water level in the reservoir. Secondly, the reservoir Lag-time (RLAG) can be estimated for use in design flood reservoir routing. Each of the two functionalities are described below

Modelling reservoir routing

The reservoir routing routine implemented in the ReFH Flood Modelling Software has been adopted from IH Report 114 by Reed and Field (1992) and requires information related to basic reservoir geometry and reservoir operating rules as shown in Figure 3.9.

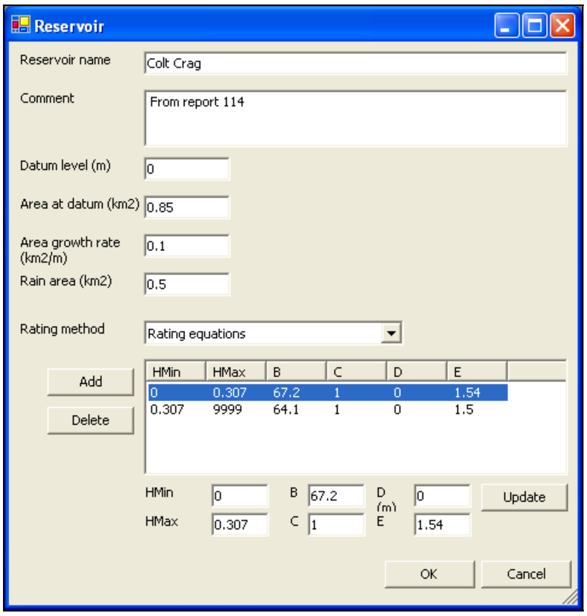

Figure 3.9 Specification of reservoir geometry and operating rules

Reservoir geometry essentially describes that rate of change of area as the water level increases. The following values are required:

- Datum level
- Area at datum
- Area growth rate
- Rain area: area of the reservoir that receives rainfall

The rating can be set up by one of two methods:

- Rating equations
- Rating table

Rating equations can be up to 20 parts, each defining the relationship between reservoir water level and reservoir outflow from water level H_{min} to H_{max} through the equation:

$$Q = B * C * (H - D)^E$$

where *H* is the reservoir level and Q the outflow. Within IH Report 114 many of the reservoirs are expressed with a single B*C value, which should be stored within the B field, with C set to 1. Rating tables can also be up to 20 parts, each defining the flow at a given water level.

Estimation of reservoir lag

The effect on a flood hydrograph when routed through a reservoir is to lag and attenuate the resulting outflow hydrograph. The more that a reservoir attenuates the inflow hydrograph the longer the duration of the most critical storm becomes, which is reflected in the adjusted equation for the critical duration as

$$D = (\mathrm{RLAG} + Tp)*(1 + \mathrm{SAAR} / 1000)$$

where *RLAG* is the reservoir lag. The procedure for estimation of RLAG implemented in the ReFH software is described by Houghton-Carr (1999) and illustrated in Figure 3.11

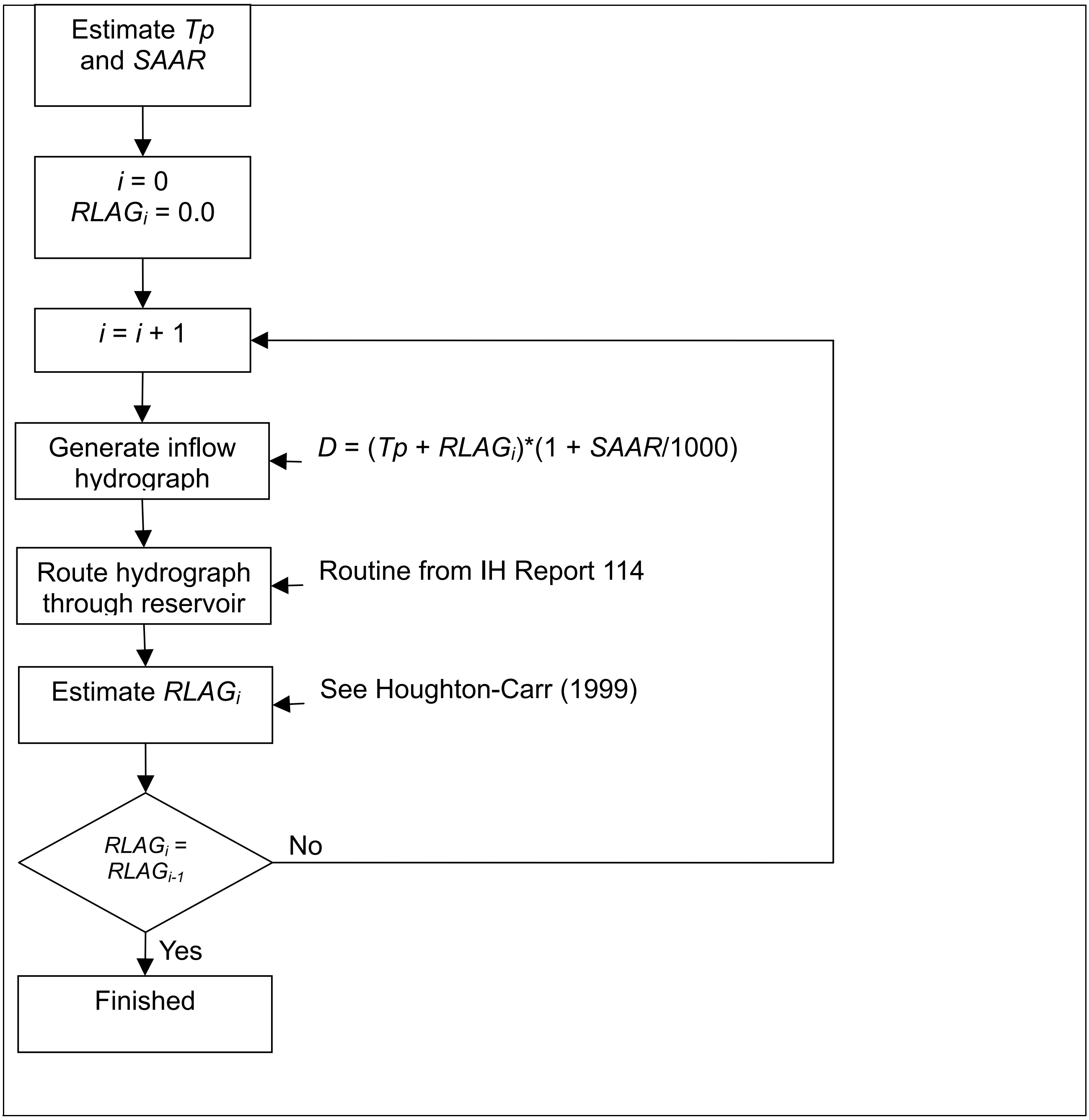

Figure 3.11 Procedure for estimation of reservoir lag RLAG

3.3 Computer requirements

The ReFH Flood Modelling software uses Microsoft's .Net framework, which is commonly installed on Windows PCs. If using an earlier version of Windows, or if the .Net framework is not installed already, the installation program will install the .Net framework on the PC, which may take some time. The minimum specifications for running the .Net framework, according to Microsoft, are:

Processor
Minimum:
600 megahertz (MHz) Pentium processor, or an AMD Opteron, AMD Athlon64 or AMD Athlon XP processor
Recommended:
800 MHz Pentium processor, or an AMD Opteron, AMD Athlon64 or AMD Athlon XP processor

Operating system
Windows 98 or above

RAM
Minimum:
128 megabytes (MB)
Recommended:
256 MB

Screen size
Minimum:
800 x 600 256 colours
Recommended:
1024 x 768 High Colour — 16-bit

4 FEH Supplementary Report No. 1

4.1 Introduction

The final component of the dissemination strategy is the publication of an application-oriented user guide to the revitalised FSR/FEH rainfall-runoff method in the form of a supplementary report to the existing five volume Flood Estimation Handbook (FEH). This report will be the first of a number of FEH Supplementary Reports that will be produced when significant changes to the FEH procedures are recommended following research.

4.2 Report contents

FEH Supplementary Report No. 1 consists of six chapters describing the ReFH model, model parameter estimation procedures, the accompanying design package for simulating design flood hydrographs and two examples of how to use the method. A description of the contents of the report is provided below:

Chapter 1: Introduction

This provides a brief introduction to the background of the revitalised FSR/FEH rainfall-runoff method and the historic development of rainfall-runoff based design flood hydrology in the UK. This chapter also provides a guide to the contents of the report.

Chapter 2: The Revitalised Flood Hydrograph (ReFH) model

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

Chapter 3: ReFH model parameter estimation

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

Chapter 4: T-year flood estimation

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

Chapter 5: Application – considerations and limitations

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

Chapter 6: Worked examples

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

References

Appendix A: The ReFH loss model

Appendix B: The ReFH antecedent soil moisture accounting model

Appendix C: ReFH model parameters for 101 catchments.

Appendix D: Calibration of the ReFH design method

5 Conclusions

The objective of this project was to disseminate the revitalised FSR/FEH rainfall-runoff method to the wider hydrological community through the production of three individual components: a free EXCEL spreadsheet implementation of the design method, a comprehensive software package supporting the ReFH model and, finally, a supplementary report to the existing five-volume Flood Estimation Handbook.

The ReFH design spreadsheet implementation of the design method was made available for download from a designated CEH website on the 19 January 2006. The interest in the free software has been very encouraging, with in excess of 250 downloads within the first months. The individuals downloading the software are affiliated to private companies, public authorities and regulators, and academic institutions.

The ReFH Flood Modelling software is a comprehensive modelling system supporting the analysis of observed flood events using the revitalised FSR/FEH rainfall-runoff method, in particular for estimation of the ReFH model parameters. The availability of a software package assisting in the parameter estimation will make it easier for hydrologists to follow best practise, i.e. to include information from relevant gauged sites when available.

Though the two remaining items, the comprehensive software and the supplementary report, have not yet been released into the public domain, it is believed that they will further facilitate the dissemination procedure. However, considering the success of the free spreadsheet, it is important to emphasis the need to adhere to best practise in flood risk analysis, i.e. to include and analyse local observed flood data where possible. This analysis cannot be carried out in the spreadsheet and access to the comprehensive software package (or another similar software implementation of the method) is necessary.

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List of abbreviations

FEH	Flood Estimation handbook
FSR	Flood Studies Report
ReFH	Revitalised Flood Hydrograph
SAAR	Standard average annual rainfall (mm)
Tp	Time to peak (hours)