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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: FD1913
2. Project title: Revitalisation of the FSR/FEH rainfall-runoff method
3. Contractor organisation(s):
   CEH Wallingford
   Maclean Building
   Crowmarsh Gifford
   Wallingford
   Oxon.
   OX10 8BB
4. Total Defra project costs: £ 232,243.00
5. Project: start date .... 01 October 2001

   end date .... 31 July 2005

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

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.

Project Report to Defra

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- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

INTRODUCTION

The FSR/FEH rainfall-runoff method is a tool for design flood estimation often used alongside statistical methods of flood frequency analysis, where estimates of complete flood hydrographs or total 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) presents a comprehensive technical restatement of the method. Despite some improvements, the basic model structure and the design estimation procedures remain largely unchanged from the first FSR version. The objective of project FD1913 was to make improvements to the key components of the rainfall-runoff method, taking advantage of new data and advances in both analytical and computational techniques.

THE REVITALISED FLOOD HYDROGRAPH MODEL

At the core of the Revitalised Rainfall-Runoff Method is the Revitalised Flood Hydrograph (ReFH) model which has 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 1 together with the required input variables and model parameters.

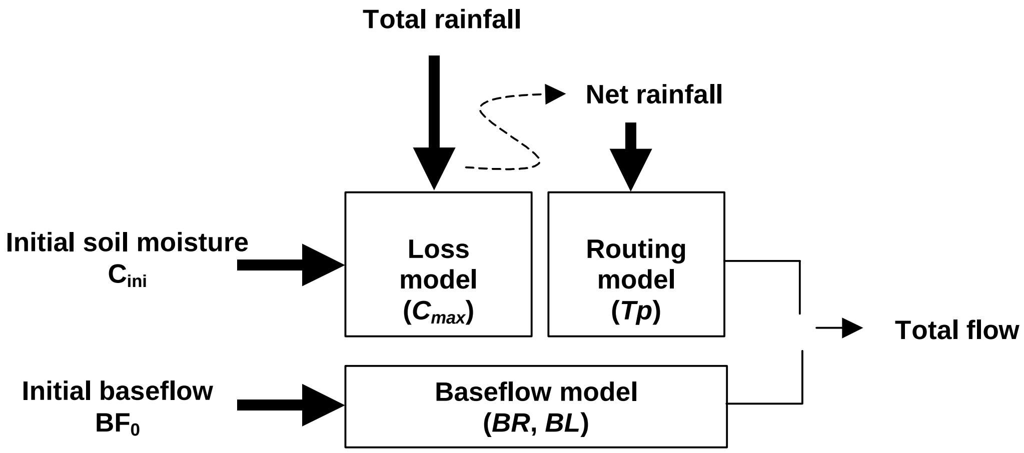

Figure 1 Schematic representation of the ReFH model

When simulating a flood event, the purpose of the loss model is 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 as specified in the routing model and, finally, the baseflow is added to the direct runoff to obtain total runoff. Details of the three model components were discussed by Stewart *et al.* (2003) and Kjeldsen *et al.* (2005a & b) and, thus, only a brief summary is given here.

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. As described by Stewart *et al.* (2003), when a rainfall volume P_t is imposed on a catchment with soil moisture content C_t, the excess amount of rainfall converted into direct runoff, qt, can be estimated as

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

where q/P is the ratio of rainfall transformed into direct runoff, i.e. percentage runoff, and C_{max} is the only model parameter and represents the maximum storage capacity of the catchment. Equation 1 is evaluated sequentially during a storm and if the soil storage is filled during an event, the percentage runoff will equal 100%. To begin the 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.

Routing model

The ReFH model uses the unit hydrograph concept for routing the net rainfall to the catchment outlet (direct runoff). 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 2.

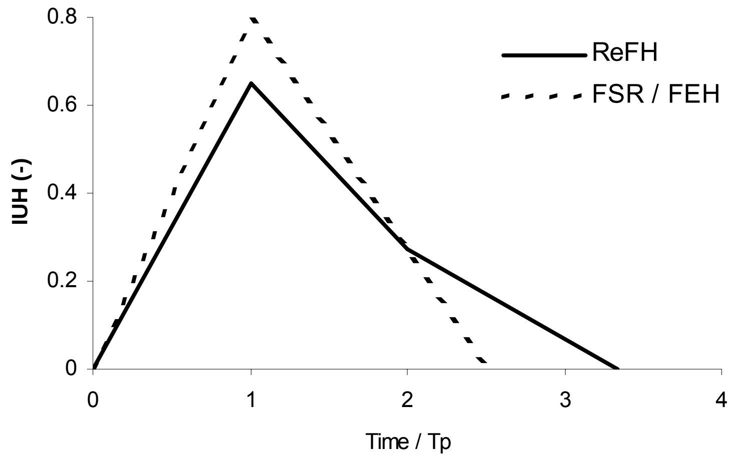

Figure 2 **Comparison of the FSR/FEH and the ReFH standard shaped instantaneous unit hydrographs**

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 textbooks.

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 surface runoff. The model can be developed as a recurrence formula and links baseflow, BF_t, to surface runoff as

$$BF_t = 1/(1-k_2)\left[k_1 q_{t-1} + k_2 q_t + (k_1 + k_2) BF_{t-1}\right] \qquad \text{for } t = 1, 2, 3, \qquad (2)$$

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; see Kjeldsen *et al.* (2005b) for further details). The actual model parameters are the baseflow recharge, *BR*, the baseflow lag, *BL*, and the initial baseflow, BF_0, i.e. flow in the river just before the onset of the flood event.

ANALYSIS OF OBSERVED FLOOD EVENTS

The ReFH model described above is defined by four parameters: C_{max}, *Tp*, *BL* and *BR*. The model was applied to 100 catchments located throughout Great Britain where a sufficient number of observed flood events (rainfall and runoff) were available. The locations of the gauging stations at each catchment outlet are shown in Figure 3. The criterion for catchment selection was that a minimum of five events should be available, of which at least one should have a peak flow exceeding QMED, the median annual flow. This selection criterion is rather more restrictive than in the original FSR study but was introduced to enhance confidence in the model's ability to simulate larger flood events.

The procedure for estimating the four model parameters consists of two stages. In the first stage, the two baseflow parameters (*BL* and *BR*) are estimated for each individual flood event by considering the recession part of the observed hydrograph. By manually selecting the end of the direct runoff and a point lower on the recession, the baseflow model parameters are optimised to fit this part of the recession. Catchment average baseflow parameters are then calculated as the average of the parameters obtained for each event. In the second stage, the loss model parameter (C_{max}) and the time-to-peak (*Tp*) parameter are estimated jointly by an optimisation scheme considering the goodness-of-fit of the modelled flood events compared to observed events summed up over all events available for the catchment. A detailed description of the optimisation procedure is provided by Kjeldsen *et al.* (2005b).

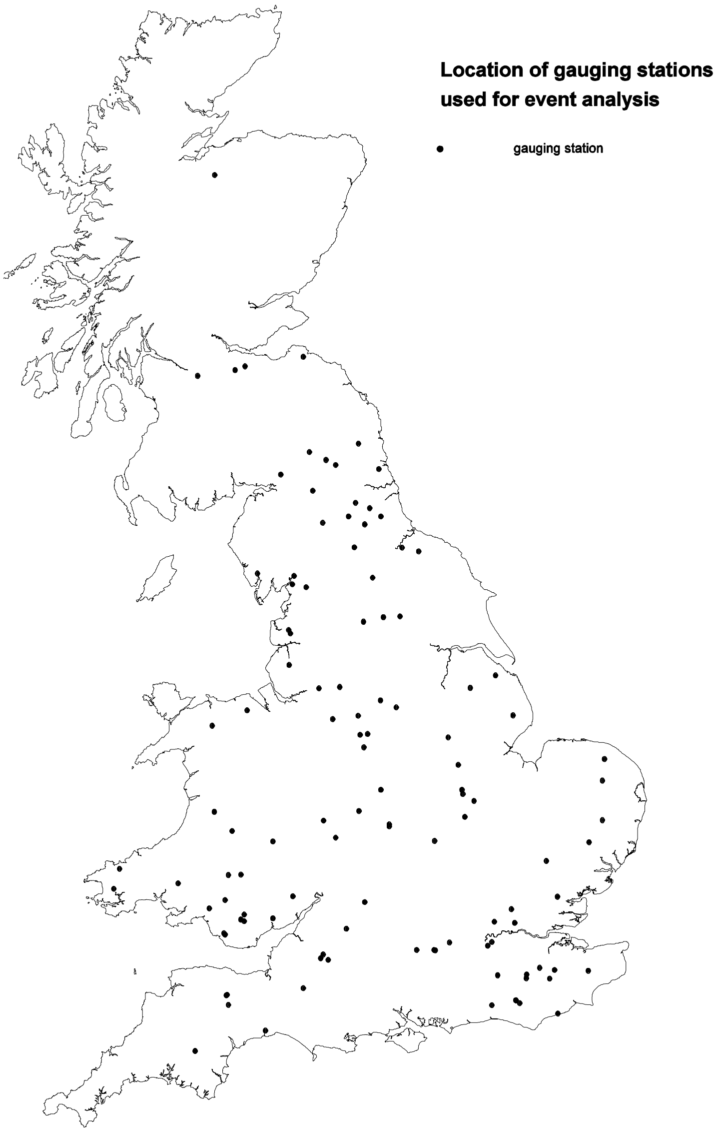

Figure 3 Locations of gauging stations used for calibration of the ReFH model

DEVELOPMENT OF A REVITALISED FEH DESIGN MODEL

A key objective of the project described here was the development of an improved rainfall-runoff method that could be generalised to allow design flood hydrographs to be derived whether or not river flow records exist at the site of interest. In this context, it is important to distinguish between the simulation of an observed flood event on a given catchment and the estimation of a design flood hydrograph. The latter is based on a design model constructed to yield the hydrograph of a specified return period when the input variables (design rainfall and design initial soil moisture content) have been specified accordingly.

The design model developed in this study is based on the ReFH model as illustrated in Figure 1. It consists of the same model elements as the ReFH model described above, but requires probabilistic values of rainfall (depth, duration and profile), initial soil moisture and initial baseflow rather than observed values. The FSR storm profiles, areal reduction factors and definition of critical duration as defined in the FSR/FEH design method remain unchanged in the ReFH design method. It is recommended that these aspects of the design method should be the subject of future research to determine whether the method could be further refined, for example, by the use of more realistic temporal profiles, especially for storms of long duration.

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. However, a key requirement of the hydrological design procedure is 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 was based on the 100 catchments where ReFH model parameters were available.

Seasonality

A concern often voiced in connection with the FSR/FEH rainfall-runoff method relates to the combination of a design storm derived from annual maximum storms (commonly encountered during the summer period) with soil conditions prevailing during the wet winter period. While this problem was resolved to some extent in the development of the FSR method through the design model calibration (the relationship between the return periods of the design rainfall and the resulting flood event), the current study has placed a greater emphasis on seasonality. Within the ReFH design method, a seasonal rainfall input combined with a seasonal initial soil moisture estimate has been introduced to ensure that the model more closely reflects the prevailing flood generating processes in the summer and winter seasons. The summer and winter seasons are defined as running from May – October and November-April, respectively. The seasonality of a catchment is determined as in the FEH method (Houghton-Carr, 1999), i.e. based on the degree of urbanisation as measured by the URBEXT catchment descriptor. On a predominantly rural catchment (URBEXT < 0.125), floods normally occur in winter whereas on urban catchments (0.125 ≤ URBEXT < 0.5) flood normally occur in summer. This definition of catchment seasonality led to the 100 catchments being split into 92 winter catchments and 8 summer catchments. The discrepancy between availability of winter and summer catchments highlights the need for inclusion of more urban catchments into the hydrometric gauging network.

Design rainfall

The ReFH method has adopted the FEH depth-duration-frequency (DDF) model (Faulkner, 1999) as the basis for deriving design storms. However, the added emphasis on summer and winter design inputs required the specification of a seasonal design rainfall input. A reworking of the FEH DDF model considering seasonal, rather than annual, maximum rainfall would be a lengthy task beyond the scope of this study. As an alternative, a seasonal correction factor was developed to convert the FEH DDF estimate of design rainfall based on annual maximum rainfall into an estimate of seasonal design rainfall as follows:

$$P_{d,i} = \lambda_{d,i} P_{d,A}, \quad \text{i = summer, winter} \qquad (3)$$

where 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 $\lambda_{d,i}$ is a seasonal correction factor depending on location, season, and rainfall duration. A detailed description of the analysis used in the development of the generic expressions of the summer and winter seasonal correction factors is given by Kjeldsen *et al.* (2005b).

Rainfall and runoff reurn periods

In the original FSR calibration, for a given flood return period, design input values of initial soil wetness (CWI), storm profile and storm duration were fixed on a catchment by catchment basis, and the return period of the design storm was chosen by optimisation. However, the current study has adopted equal return periods for the design storm depth and the resultant design flood. Thus, the 100-year flood is generated by the 100-year rainfall rather than the 140-year rainfall as in the FSR/FEH method. This brings the method into line with hydrological design practice for urban areas in the UK.

Based on this decision, within the calibration of the design model the initial soil moisture content (C_{ini}) became the only remaining free variable. However, allowing the design value of C_{ini} to vary could potentially produced unrealistic values and consequently it was decided to introduce a calibration parameter α_T in the loss model such that the design loss model (as opposed to the loss model used for analysing observed events) is given as

$$q_t / P_t = \begin{cases} \alpha_T \left(C_{ini} / C_{max} \right) + P_t / 2C_{max} & t = 1 \\ \left(C_{t-1} / C_{max} \right) + P_t / 2C_{max} & t = 2, 3 \ldots \end{cases} \quad \text{and} \quad C_{t+1} = C_t + P_t \qquad (4)$$

where α_T depends on the return period under consideration. Design estimates of C_{ini} are derived by assuming $\alpha_5 = 1$, i.e. the C_{ini} value required to reproduce the 5-year flood without any adjustment made to the loss model as described later.

Design model calibration

The existing FSR/FEH method has been criticised for overestimating design floods when compared to the corresponding estimates obtained through a statistical analysis of annual maximum (AMAX) flood peak data. Consequently, the ReFH design method has been calibrated to ensure that the flood frequency curves derived from the method correspond to flood frequency curves derived through statistical analysis of AMAX data. To ensure consistency, the FEH statistical method (Robson and Reed, 1999) was applied to AMAX data from HiFlows-UK for each of the 100 catchments in the dataset. The pooled statistical analysis was carried out using automated procedures developed by Morris (2003).

The calibration procedure was 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 the T-year design rainfall) and the corresponding T-year estimate obtained from the pooled analysis (as illustrated in Figure 4) is minimised by adjusting the calibration parameter α_T, i.e.

$$\min_{\alpha_T}\left\{\left(\frac{Q_{T,ReFH}(\alpha_T)-Q_{T,Stat}}{Q_{T,Stat}}\right)^2\right\}=\min_{\alpha_T}\left\{d_T^2(\alpha_T)\right\} \qquad (5)$$

where T is the target return period, α_T 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).

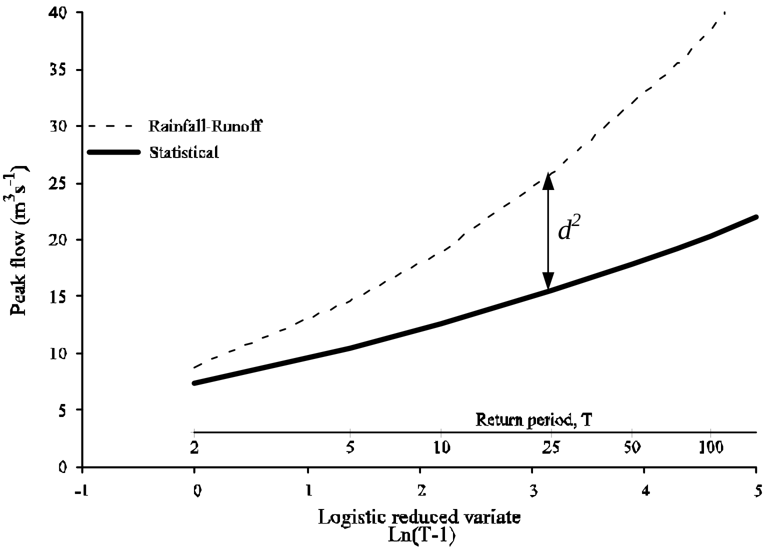

Figure 4 **Difference between flood frequency curves derived from FEH pooled statistical method and from the ReFH model (calibration performed by minimising d^2 for each return period)**

The calibration procedure was carried out for each of the 100 catchments for the summer and winter seasons. For each season the corresponding seasonal rainfall correction factor was applied and a seasonal estimate of initial baseflow was used.

To enable the ReFH design method to be applied to any catchment in the UK, the calibration procedure was carried out in two stages. First, the minimisation in Equation 5 was used to estimate the C_{ini} value required to reproduce the 5-year flood on each catchment with $\alpha_5 = 1$. The resulting C_{ini} value is taken as the design input value of initial soil moisture content at all other return periods. The choice of the 5-year return period as a reference point for the calculation of C_{ini} is arbitrary but does correspond with the return period chosen in the derivation of the seasonal rainfall correction factors. A comparison between values of C_{ini} derived from observed flood events and the design values of C_{ini} found that the design values generally compares well to the C_{ini} values of the largest observed flood event on record for each catchment (Kjeldsen *et al.*, 2005b). In the second stage, using the derived C_{ini} values as input, estimates of α_T were obtained for each catchment for each return period using the minimisation procedure in Equation 5.

Multivariate linear regression was used to relate the calculated values of C_{ini} at each site to relevant catchment descriptor values to allow the final method to be applied to ungauged sites. The predictor equations for winter and summer initial soil moisture content are given by

$$C_{ini,winter} = \frac{C_{max}}{2}\left(1.20 - 1.70BFIHOST + 0.82PROPWET\right)$$
$$C_{ini,summer} = \frac{C_{max}}{2}\left(0.90 - 0.82\,BFIHOST - 0.43PROPWET\right) \quad (6)$$

where C_{max} is the maximum soil moisture capacity. The final design values of α_T were derived for a range of return periods as the average of the values obtained for each of the 100 analysed catchments within each season. The design values of α_T are shown in Figure 5 for the winter and summer seasons, respectively.

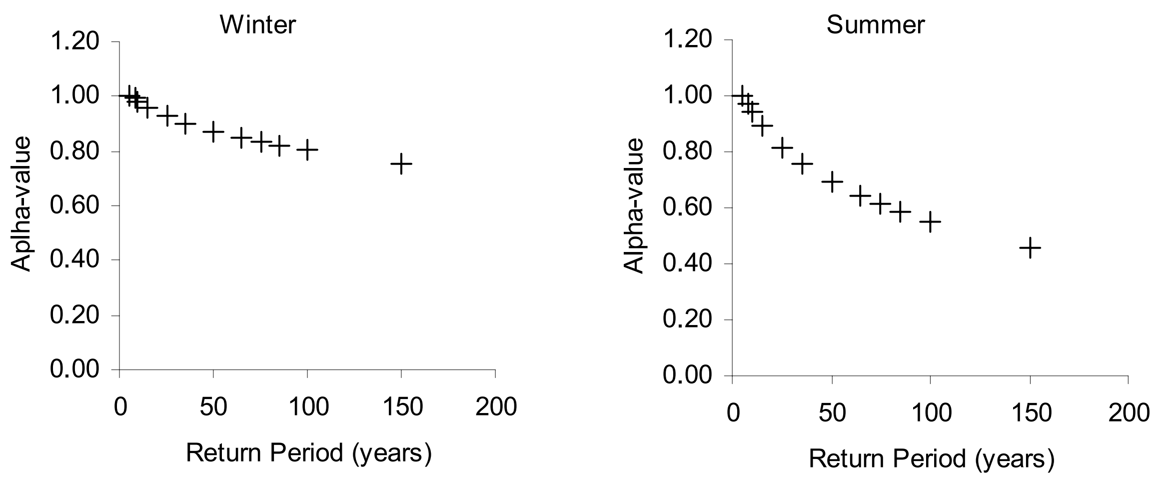

Figure 5 **Alpha coefficients for winter and summer conditions**

To use the design model, the user is required to set up the ReFH model and then specify design input values of rainfall (depth, duration and profile) and initial soil moisture content (C_{ini}) in order to generate the T-year flood. As the α_T values depend only on the required return period, the value does not vary from catchment to catchment.

APPLICATION OF THE ReFH DESIGN METHOD

To illustrate the application of the ReFH design method, example results from four of the catchments analysed are given here. At each site the four ReFH parameters were obtained from direct analysis of observed flood events and are shown in Table 1. In Table 2 the relevant catchment descriptors necessary for applying the design model are shown. The last column in Table 2 shows the C_{ini} values calculated using Equation 6.

Table 1: ReFH model parameters

Station	C_{max} (mm)	*Tp* (hours)	*BL* (hours)	*BR* (-)
30004	625	6.2	81.8	1.35
39012	686	2.1	38.1	1.13
54011	332	8.9	26.5	0.54
72002	189	4.2	23.8	0.65

Table 2: Relevant catchment descriptors and initial soil moisture content

Station	AREA (km2)	SAAR (mm)	BFIHOST	PROPWET	URBEXT	Cini (mm)
30004	59.94	685	0.570	0.29	0.0110	144
39012	72.89	671	0.599	0.30	0.2064	82
54011	186.20	666	0.523	0.28	0.0496	87
72002	276.56	1253	0.369	0.56	0.0057	89

Flood frequency curves derived from the ReFH design method are compared to flood frequency curves obtained from the pooled statistical analysis and the FEH rainfall-runoff method, respectively in Figure 6. Note that for each catchment the ReFH flood frequency curve was derived using both summer and winter design conditions, although in practice only one of the options should be used based on the URBEXT value of the catchment.

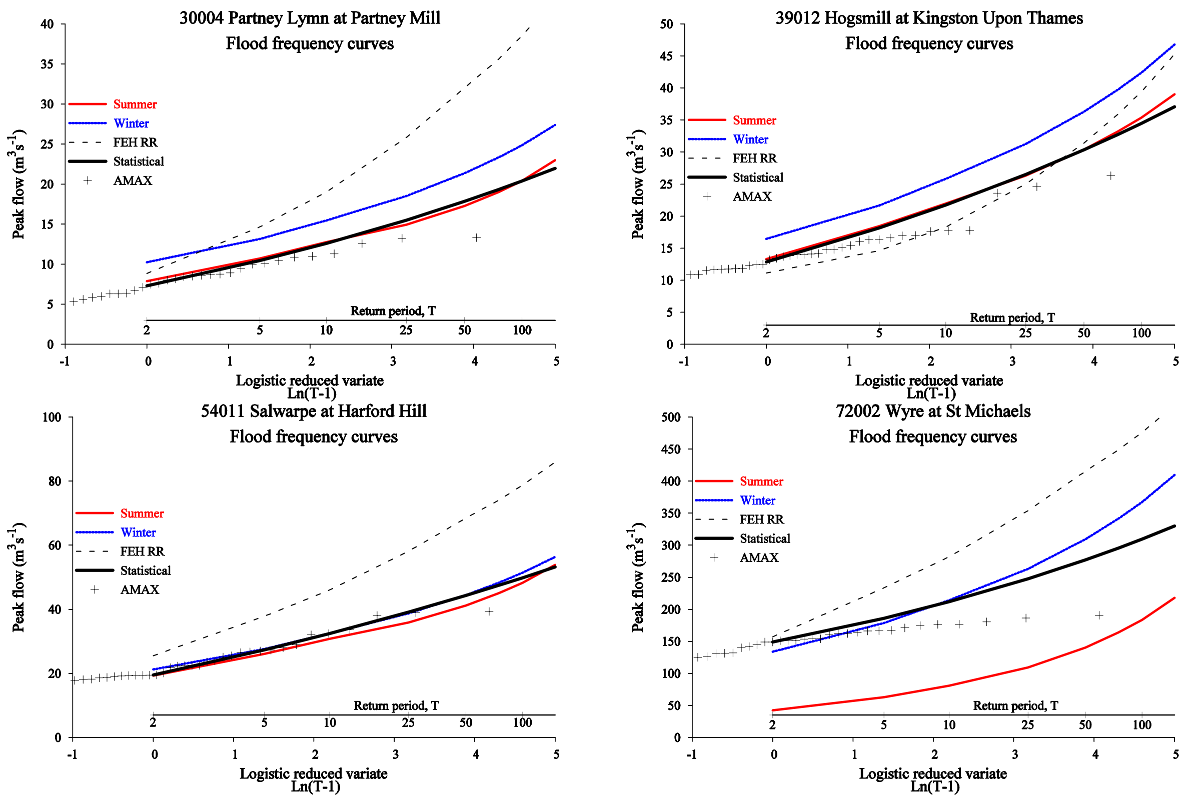

Figure 6 **Comparison of flood frequency curves obtained from the ReFH model (summer and winter), the FEH rainfall-runoff model and pooled statistical analysis**

The comparison generally shows that the ReFH model produces flood frequency curves (FFC) more aligned with the pooled statistical procedure and the observed AMAX data than the FSR/FEH model. For catchment 30004, the modest URBEXT value of 0.0110 indicates an essentially rural catchment and, hence, the winter design input values should be applied even though the summer design values appear to give a better fit to the pooled statistical FFC. In contrast, the winter design input values are shown to produce a close fit to the pooled statistical FFC for catchment 72002, which is a large, wet and essentially rural catchment located in north-west England and therefore would be expected to be dominated by winter flooding. Catchment 39012 is a heavily urbanised catchment located in south-east England and, therefore, the flood regime for this catchment would be expected to be dominated by summer flooding. For this catchment the summer design conditions are shown to produce the closest fit to the statistical FFC, which is reassuring. For catchment 54011, the summer and winter design conditions yield similar results, although the winter design conditions should be applied due to the slightly urbanised (URBEXT = 0.0496) nature of the catchment.

POSSIBLE FUTURE WORK

The ReFH model is considered to be a significant step forward in terms of developing a more physically-based approach for 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 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 account 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 more seasonally-varying input parameters into the 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 the users of the methodology with a practical tool. However, further research could beneficially be targeted at a more comprehensive investigation, particularly 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 catchment under consideration, but independent of return period. These simplifying assumptions (with the associated loss of precision) were introduced to reduce the complexity of the problem and to allow the development of a practical tool. However, a more comprehensive study would be needed to develop a seasonal DDF model through 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 durations, temporal profiles and 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 project, as well as the additional data collected since the development of these concepts 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.

ACTIONS RESULTING FROM RESEARCH
The outcome of this research project is expected to replace the existing FSR/FEH rainfall-runoff model described in FEH Vol.4. As a direct result, the Environment Agency has commissioned CEH to undertake a dissemination project, developing a software application supporting the practical use of the method as well as publication of a supplementary report to the FEH, effectively replacing the existing Vol. 4 (Project SC040029).

CONCLUSIONS
The ReFH rainfall-runoff method offers a range of improvements to the FSR/FEH rainfall-runoff methodology for design flood estimation. Firstly, the ReFH model is based on hydrological modelling principles where model parameters are related to physical properties of the catchments under consideration. Secondly, the development of the design procedure has been based on an updated version of the Flood Event Archive used in the original FSR study. In particular, more recent large events have been added to the archive as part of this study. This should give more confidence in the extrapolations needed for estimating design floods of high return periods. Finally, the new design method has introduced a more comprehensive consideration of seasonal flooding than was included in the FSR/FEH model.

The FSR/FEH model has been available for 30 years and as a consequence a large body of experience is available. Obviously, the newly-developed ReFH model cannot match this wealth of experience, but with the introduction of a more generic modelling system, there is scope for further improvements based on scientific considerations and this is considered to be a real benefit of the project.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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