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Reservoir Safety - Floods and Reservoir Safety

Clarification on the use of FEH and FSR design rainfalls

Final Report

Babtie Group
In association with:
CEH Wallingford
Rodney Bridle Ltd

BWA 200601 14/08/00

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27 September 2000

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Dear Sir

Floods and Reservoir Safety - Clarification on the use of FEH and FSR design rainfall
Final Report

In accordance with your project specification of 29 March 2000 we are pleased to submit our final report entitled "Floods and Reservoir Safety – Clarification on the use of FEH and FSR rainfall".

Yours faithfully

A Macdonald
Director

djp

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DETR
Reservoir Safety - Floods and Reservoir Safety
Clarification on the use of FEH and FSR design rainfalls

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1 Introduction

The Flood Estimation Handbook (FEH) and its associated software were published by the Institute of Hydrology in late 1999. It gives guidance on rainfall and river flood frequency estimation in the UK, and as such largely supersedes the Flood Studies Report (FSR) of 1975. Although FEH does not present a new approach for reservoir flood estimation it does introduce a new means of calculating a design rainfall depth, which is one of the key inputs used in UK reservoir flood estimation. (Changes in the rainfall depth can affect significantly the size of resulting flood estimates that are used in design and assessment of overflow works).

Inevitably the sizes of the new design rainfall depths calculated by FEH have been compared to equivalent FSR predictions. A study by Macdonald and Scott (2000), in which a relatively small sample of reservoir catchments was assessed, found that although FEH and FSR rainfall depths associated with 5-year events are similar in magnitude they do appear to significantly diverge for the 10,000-year events. Of potential concern to the dams community is that the FEH 10,000-year design storms appear systematically larger than those of the FSR method by a surprisingly large amount. Indeed the depths were shown in some instances to exceed the FSR's estimated Probable Maximum Precipitation (PMP) depths. However no comparative information was presented for the other key return periods that are of interest to the panel engineer, viz the 1000-year and 193-year[1] events.

Although FEH Volume 4 devotes a chapter to reservoir flood studies, use of the FEH design rainfall is implied rather than stated. Some qualification upon the suitability of the FEH design rainfall procedure is, however, given in Volume 2.

The objectives of this project are to give the DETR advice and clarification on:

1. The rationale for the different outcomes of the FEH and FSR rainfall depth estimation methodologies.
2. Whether the comparisons and the rationale are likely to be generally typical for reservoirs across Britain.
3. The extent of revisions which may (as a consequence of the findings of the first two objectives) be required to the third edition of 'Floods and Reservoir Safety'(FRS) (ICE, 1996).
4. How such a revision, if necessary, might be undertaken.
5. What, if any, interim guidance can usefully be given to reservoir panel engineers regarding the use of Floods and Reservoir Safety in light of the FEH.

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[1] In the FSR rainfall-runoff method the 193-year design rainfall event is used to synthesise the 150-year design flood event.

Section 2 of this report investigates the scale of the T-year differences between the FEH and FSR rain depth estimates. This section also discusses the rationale behind the differences. Section 3 extends the reservoir catchment analysis of Macdonald and Scott and briefly discusses the issues associated with PMP. Section 4 focuses upon the implications of Sections 2 and 3 for 'Floods and Reservoir Safety' and discusses how a provisional revision might be undertaken. Section 5 offers interim guidance to Panel Engineers and reservoir owners on what actions to take in light of the FEH and prior to the findings of the recommended research. Section 6 identifies technical research recommendations.

The project team appointed by DETR includes reservoir engineers to represent potential users of FEH and hydrologists as the providers of the rainfall estimates which are used by the reservoir engineers. The reservoir engineers are from Babtie Group assisted by RC Bridle, and the hydrologists are from the Centre of Ecology and Hydrology (CEH) and from Babtie Group. CEH is the successor organisation to the Institute of Hydrology which produced the FEH.

It should be noted that FEH does not present a new method for the estimation of PMP. Where PMP estimates are mentioned in the report they are always those calculated by the FSR methodology.

Although not within the remit of this project it should also be noted that certain aspects of the estimation of the T_p (Time to peak) and PR (Percentage Runoff) unit hydrograph parameters have also been revised in the FEH. The influence of these revisions to flood studies are not considered in this project, and they are thought to be typically a much smaller influence than the changes in rainfall depth estimation.

2 Technical review of FEH and FSR comparisons

2.1 Stimulus to technical review

Rainfall frequency estimates in the UK are principally based on the Flood Studies Report (NERC, 1975). The FSR methods have been incorporated in procedures for reservoir safety, storm-sewer and some agricultural designs, in addition to their mainstream use in rainfall rarity assessment and rainfall depth estimation for river flood design.

The recently published Flood Estimation Handbook (IH, 1999) supersedes most of the FSR. In particular, Volume 2 of the FEH presents a new generalised rainfall frequency estimation procedure for the UK[2]. The procedure is presented in the form of a rainfall depth-duration-frequency (DDF) model. Section 2.4 of that volume indicates that the model has been fitted to rainfall estimates derived for durations between one hour and eight days, and for various return periods up to 1000 years. In particular it states: "The model is designed to provide consistent estimates for return periods up to 10,000 years, although estimates for return periods this long are inevitably extrapolations." This statement has given rise to some discussion. It is now recognised that "consistent" is too strong a word, and a corrigendum has been issued (on the FEH website) to replace it by "internally consistent". What the statement means is that the DDF model has been devised to ensure that there are no internal contradictions. (An example of a contradiction would be if the estimated 1000-year 6-hour rainfall depth exceeded the corresponding 7-hour rainfall depth.)

Improving methods of reservoir flood estimation was not an explicit objective of the FEH programme. The research for Volume 2 was initially restricted to the return period range 2 – 200 years. Later, in consultation with the FEH Advisory Group, the client modified this to 2 – 2000 years. There is uncertainty as to whether the FEH rainfall frequency procedure should supplant the FSR rainfall frequency procedure in UK reservoir flood safety assessments. The 193, 1000 and 10,000-year rainfall depths are used in estimating the 150, 1000 and 10,000-year reservoir design floods by the rainfall-runoff method (see Volume 4 of FEH).

A disclaimer given in each volume of the FEH states "Neither the named authors nor the Institute of Hydrology nor its parent bodies have approved any instruction that use of FEH procedures be made mandatory for particular applications". Such instructions are thought, by the authors of FEH and by precedent, to be a matter for the relevant professional or political body. In the case of reservoir safety guidance this is given by the

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[2] The procedure has been developed for the estimation of T-year events. It does not revise Probable Maximum Precipitation (PMP) estimates. The FSR PMP methodology remains the only generalised procedure for PMP available for the UK.

Institution of Civil Engineers (ICE) and the Department of the Environment, Transport and the Regions (DETR), the Scottish Executive, and the Welsh Assembly.

The issue – of how to respond to publication of the FEH with respect to reservoir safety assessment – has been raised by a number of reservoir owners and reservoir engineers. The first published comparison was by MacDonald and Scott (2000), who presented a brief comparison of FEH and FSR estimates of design rainfalls for particular reservoirs. They reported that many estimates are significantly increased, with implication for the perceptions of risk associated with spillway design flood exceedance.

2.2 Differences in FEH and FSR estimated rainfall depths

The FEH method of rainfall frequency estimation (Faulkner, 1999) was devised to be fully digital. To facilitate comparisons, an earlier digital implementation of the FSR method was adopted. This is based on digitised versions of the relevant FSR paper maps (chiefly, M5-2day and Jenkinson's r) and formulae given by Keers and Westcott (1977). Spot checks suggest that this is a generally faithful implementation of the original hand-calculated FSR method.

The comparisons are presented in the form of mapped ratios for key return periods (193, 1000 and 10,000 years) and representative durations (1 hour, 6 hours and 1 day). For example, Figure 1 presents the FEH/FSR ratio for the 193-year 1-hour rainfall estimates. For this return period and rainfall duration it is seen that the FEH procedure is giving substantially higher estimates, except in parts of eastern Scotland. The FEH estimates are seen to be more than 50% greater than the FSR estimates in many upland areas in the west and in much of eastern England. The pattern is broadly similar, but the differences are more marked for 1-hour rainfalls of longer return period (see Figures 2 and 3).

Figures 7 – 9 show mapped FEH/FSR ratios for 1-day rainfall depths of 193, 1000 and 10,000-year return periods respectively. The maps show that at long return periods FEH rainfall frequency estimates are higher than FSR rainfall frequency estimates in much of Britain.

The ratios are greater at 10,000 years than at shorter return periods for each of the three durations. They are at their most dramatic for the 10,000-year 1-hour rainfall depth (Figure 3).

The ratios for the intermediate return period of 1000 years (Figures 2, 5 and 8) are intermediate to those for the 193 and 10,000-year return periods. The ratios are less pronounced for the intermediate duration of 6 hours (Figures 4, 5 and 6) than for either the 1-hour or 1-day duration: something that is confirmed by the geometric mean ratios quoted in Table 2.1.

Duration	Return period		
	193 years	**1000 years**	**10,000 years**
1 hour	1.37	1.52	1.74
6 hours	1.13	1.19	1.29
1 day	1.23	1.28	1.34

Table 2.1 Geometric mean ratios of FEH to FSR design rainfall estimates for Britain.

It is evident that the FEH procedure is giving larger design rainfall depths (for return periods relevant to reservoir safety) throughout much of Britain, the chief exception being parts of eastern Scotland. The relative differences are typically greatest at the shortest duration (1 hour) and the longest return period (10,000 years) considered here. From Figure 3 it is seen that 10,000-year 1-hour rainfall estimates by the FEH are more than double those by the FSR throughout much of eastern England south of the Humber.

There is legitimate concern at the scale of these differences.

2.3 Exploring the basis of the differences

2.3.1 FSR method

Prior to publication of the FEH, the FSR rainfall frequency method has generally been thought to be satisfactory on average but lacking important spatial detail. For example, it has long been held to underestimate rainfall frequency depths in the Bridgwater district of south west England (Bootman and Willis, 1977). Dales and Reed (1989), and others, have suggested that the FSR method is excessively generalised, in the sense that local and regional differences in rainfall frequency are not fully represented.

The storm-sewer industry has become accustomed to short-duration design rainfall depths that change very little from place to place, as exemplified by the map of 5-year 60-minute rainfall derived for the Wallingford Procedure. This indicates a design value of 18-22 mm throughout most of England. Yet May and Hitch (1989) found pronounced fluctuations in the 5-year 1-hour rainfall depth between about 13 and 22 mm (equivalent to a 5-year 60-minute depth of about 15-25 mm) in an elongated study region from East Sussex to the Peak District. They concluded that "The 5-year 1-hour rainfall in south-east England (at least) has a more complicated structure than is indicated by the map in the FSR and its digitized version." While May and Hitch did not study rainfall growth rate variations (e.g. the ratio of 1000-year to 5-year estimates), their work highlighted the lack of spatial detail in the FSR estimates.

2.3.2 FEH method

The FEH rainfall frequency procedure is radically different. There are three main ingredients:

- The mapping of the index variable, RMED (Mean annual maximum rainfall)[3].
- Rainfall growth estimation by the FORGEX (FOcused Rainfall Growth curve EXtension) method[3].
- Their combination in a 6-parameter rainfall depth-duration-frequency (DDF) model[3].

The RMED and FORGEX parts of the procedure have been published in the peer-reviewed literature (Prudhomme & Reed 1998, 1999; Faulkner & Prudhomme 1998; Stewart *et al.* 1999; Reed *et al.* 1999; Faulkner & Jones 1999).

The mapping of the index rainfall (RMED in the FEH) builds in topographic and marine influences on extreme rainfalls, as an aid to interpolation between gauged estimates of RMED. This contrasts with the approach taken in the FSR, where the interpolation of the index variable was aided by pre-existing maps of average annual rainfall, themselves aided by subjective judgements of topographic effects by experienced meteorologists. The FORGEX method differs fundamentally from the approach taken to derive rainfall growth factors for the FSR. A driving force behind FORGEX is the use of a spatial dependence model to aid the extrapolation of the rainfall growth curve to long return periods.

In reviewing the scope for the FEH rainfall procedure to be flawed at long return periods, some thought has been given to a possible interaction between the RMED mapping and the FORGEX rainfall growth estimation. It is noted that the RMED mapping procedure takes detailed account of the local topography as is evident in the relatively detailed maps of RMED presented in the FEH (for example, Figure 7.2 of Volume 2). In contrast, topographic effects play no direct role in the selection of gauges used in the derivation of the rainfall growth curve at a particular point. The selection criteria are based on distance alone. The point at issue is whether rainfall growth factors at upland sites are adequately represented by pooled observations from gauges which, in many cases, will be at adjacent lowland sites rather than adjacent upland sites (the available network of gauges is sparser in upland than lowland areas). Thus, one hypothesis is that the *T*-year rainfall depths in upland areas are being estimated as the product of an index rainfall – which adequately reflects topography – and a rainfall growth factor – that possibly does not. It has not been possible to test this hypothesis during this brief review. However, it is noted that the greatest relative differences in the FEH and FSR estimates occur in lowland areas of eastern England, on which the above hypothesis would have no bearing. Thus, this factor is not responsible for the major differences in FEH and FSR estimates for the south east of England, confirmed in Section 2.2.

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[3] DDF, RMED, FORGEX are defined in the glossary appended to this report.

The least researched part of the FEH rainfall frequency procedure is the rainfall depth-duration-frequency (DDF) model. This is a 6-parameter model fitted to exhaustive evaluations of the index rainfall (RMED) and the rainfall growth factors (by FORGEX) at sites across the UK. Section 10.4 of Volume 2 lists the durations and return periods at which the over-arching DDF model was fitted. These are: durations of 1, 2, 6, 12 hours and 1, 2, 4, 8 days, and return periods of 2, 5, 10, 20, 50, 100, 200, 500 and 1000 years. As Figure 10.5 of FEH Volume 2 illustrates, the effect of fitting the DDF model to design rainfalls for a particular site is to impart some limited smoothing which has the specific benefit of avoiding the type of internal contradiction referred to in Section 2.1 of this report.

However, the imposition of a particular DDF model structure, and the manner of its fitting, are significant matters that warrant further investigation. Section 10.3.3 of Volume 2 draws attention to the fact that the DDF model imposes a particular functional form on the relationship between rainfall depth (R) and return period: namely, that $\ln R$ follows a Gumbel distribution. Thus the choice of the DDF model structure is a prime candidate when looking to explain the "strong" behaviour found - in comparison to the FSR – when the FEH rainfall frequency procedure is applied at long and very long return periods.

2.4 Review of depth-duration-frequency (DDF) model

2.4.1 Model structure

The rainfall DDF model seeks to represent design rainfalls over a wide range of durations and return periods, using just six parameters. A separate model is provided at each 1 km grid point across the UK. For clarity, the equation numbers used here are taken directly from FEH Volume 2.

The FEH rainfall DDF model takes the composite form:

For $D <= 12$ hours:

$$\ln R = (cy + d_1)\ln D + Ey + f \qquad [2.1]$$

For $12 < D <= 48$ hours:

$$\ln R = \ln R_{12} + (cy + d_2)(\ln D - \ln 12) \qquad [2.2]$$

For $D > 48$ hours:

$$\ln R = \ln R_{48} + (cy + d_3)(\ln D - \ln 48) \qquad [2.3]$$

Here, R denotes rainfall depth (mm), D is the rainfall duration (h) and y is the Gumbel reduced variate. R_{12} denotes the 12-hour rainfall depth from Equation 2.1, and R_{48} denotes the 48-hour rainfall depth given by Equation 2.2.

The six parameters are d_1, d_2, d_3, c, E and f. For clarity, the lower case e used in FEH Volume 2 has been replaced by E, so that it cannot be confused with the exponential constant, e. Substituting $D = 1$ in Equation 2.1, it can be seen that the parameter E is the gradient of a log-Gumbel distribution:

$$\ln R = \mathrm{E}y + f$$

Given that the most dramatic differences between the FEH and FSR generalisations are at the 1-hour duration, it is particularly relevant to explore the E parameter.

2.4.2 DDF model-parameter variation across Britain

To facilitate clearer understanding of the FEH rainfall DDF model, its parameter values were mapped across Great Britain (see Figures 10 – 15). Attention focuses on the c and E parameters, which control the growth rates (i.e. the variation with the Gumbel reduced variate, y); see Equations 2.1 – 2.3.

The parameter c is mapped in Figure 13, while Figure 14 shows the variation in E. These figures give rise to two particular concerns. First, there is clear evidence of marked parameter interaction between the c and E parameters. This is most obvious in the anomalies which appear in central and eastern Scotland in Figures 13 and 14. The other cause for concern is the unnatural boundary features evident in the maps of these two variables, especially for the E parameter where an arc at a radius of about 200km from London can be seen (Figure 14). The reason for these boundaries are complex but understood. In brief, they arise from a feature of the FORGEX method (specifically, its imposition of a maximum radius beyond which data are not pooled) and a feature of the network of gauges for which annual maximum rainfall data are available (specifically, the much higher density of observations in some areas, e.g. London).

The findings suggest that there is need of a recalibration of the FEH rainfall DDF model to reduce or eliminate the parameter interaction evident in Figures 13 and 14. It should not be assumed that the recalibration will lead to greater conformity with the FSR estimates. Faulkner (pers comm 2000) notes that many of the spatial features evident in the ratio maps of FEH:FSR depth estimates are also present in ratio maps of the FORGEX:FSR growth estimates (e.g. compare Figures 1 and 3 from this report with Figures 9.5 and 9.12 from Faulkner and Prudhomme, 1997). Thus, the main features (of the FEH:FSR ratios) are thought to reflect the underlying methods, rather than the choice of DDF model structure.

The findings also suggest that it could be helpful if research were undertaken to explore the sensitivity of design rainfall estimates by the recalibrated DDF model to gauged network density and the maximum distance feature incorporated into FORGEX. This second topic is thought to be a more complicated but less significant aspect. It has greater relevance to drainage designs in south-east England than to typical reservoir safety assessments in north and western Britain. The strong pull that rainfall records in greater London are exerting on rainfall frequency estimates in south-east England might warrant a prior study. A feature of the FORGEX method is that extreme events which have been observed at particular sites "diffuse" to influence rainfall estimates at other locations in the region. This is a pioneering feature of the FORGEX method. The method is inevitably sensitive to the density of observations, however the feature is an important asset of the FORGEX method.

2.5 The wider context

The rainfall frequency procedure given in FEH Volume 2 has two primary applications. The first is to supply design rainfall estimates for use with the FSR rainfall-runoff method of flood estimation. This method is sustained by FEH Volume 4, with extensive re-writing but relatively minor modification. The second mainstream application of the FEH rainfall procedure is in assessing the rarity of particular rainfall events: for example, when reviewing flooding incidents or assessing wet-weather claims.

It is important to note that the FEH rainfall procedure has been fully and effectively implemented as part of the FEH CD-ROM software package. The software package is attracting considerable interest, and it is likely that the package will come to the attention of users with rainfall frequency estimation requirements in other areas: for example, in storm-sewer design. In this respect, there is a potentially wide interest in how the FEH rainfall frequency procedure performs at short durations, i.e. at one hour and below.

Estimation of extreme rainfall depths – such as the 10,000 year rainfall – is of relevance to risk assessments for other sensitive structures (e.g. nuclear installations) as well as for dams.

In sending out any message to users about the extent to which FEH rainfall estimates of long return period should be considered provisional, it will be important for Government and/or the Institution of Civil Engineers to be aware of the wider context in which rainfall frequency estimates are required.

2.6 Discussion

The ratios of FEH to FSR rainfall frequency estimates are mostly greater than one. The ratios lie on average between 1.3 and 1.7 for the design return periods and rainfall durations relevant to reservoir safety. These GB-average ratios mask wide regional variations. For short-duration extreme (e.g. 1-hour) rainfalls in south-east England, the ratios are typically greater than 2.0. Thus, it is concluded that the FEH method is yielding rainfall estimates that are seriously greater than those currently used in reservoir flood assessments. The implications of accepting the FEH estimates are obvious. Either a higher perceived risk of a design exceedance will have to be tolerated, or extensive remedial works will be required to bring UK reservoirs up to the nominal risk standards recommended by the ICE.

It is relevant to note that the Dales and Reed (1989) research – which led to the FORGE method of rainfall growth estimation and, later, the FORGEX method – was motivated by reservoir safety concerns. The research was designed to test the notion that a 60-year absence of major design flood exceedance at any of more than 1000 major impounding reservoirs might be a natural phenomenon rather than a sign that spillway design floods were conservatively high. Dales and Reed found that spatial clustering in UK reservoirs (in relation to the typical size of flood-producing storms) leads to an expected pattern in which many years pass between exceedances, before exceedances occur simultaneously at a number of sites, in response to the same storm or storm system. Although not explored by Dales and Reed, it is to be expected that antecedent catchment wetness effects accentuate the spatial dependence feeding through from that in rainfall. When the conditions are ripe for an extreme storm to yield an extreme flood, it is likely that the conditions will also be ripe at other sites locally, regionally or nationally. This is relevant both as a renewed warning (against the notion that UK spillway design floods are conservatively high) and as a reminder that the FEH rainfall frequency method differs from the FSR method in part because it explicitly allows for spatial dependence in rainfall extremes.

In communicating to others inside and outside the dams safety community, it is important to be clear that publication of the FEH has not increased the actual risk of a flood occurring that a UK reservoir cannot safely discharge; it is the same this year as last year. However, if the new rainfall frequency method is adopted, the FEH will in many cases change reservoir owners' and inspecting engineers' evaluations of the risk, as clearly illustrated later in Tables 3.2 and 3.3.

A rainfall event thought to have exceeded estimated Probable Maximum Precipitation (PMP) was observed at Walshaw Dean Lodge in the Calderdale storm of 19 May 1989. Assessed using the FEH rainfall frequency procedure, the recorded fall of 193 mm in 2 hours in this part of West Yorkshire has a return period of 6000 years (see FEH Volume 2, Section 15.6). Geomorphological scarring of the landscape confirmed that this was an exceptionally rare event on Greave Clough: a small unreservoired tributary east of Widdop Reservoir and west of the Walshaw Dean Reservoirs. Nevertheless, the FEH assessment of the return period of this extreme rainfall may not be excessively short.

3 Comparison of estimates for example reservoired catchments

3.1 Catchment comparisons

Macdonald and Scott compared FEH 10,000-year catchment rainfall depth estimates to both the equivalent 10,000-year and PMP estimates of the FSR. Predictions for ten reservoired catchments in England and Wales were presented. Their findings suggested that the FEH 10,000-year rainfalls were significantly larger than the corresponding estimates computed from the FSR methodology, and that in some cases the FEH 10,000-year estimates were also higher than the FSR PMP values.

Since only a relatively small number of examples were studied by Macdonald and Scott, and Scottish sites were not represented, it was agreed that further reservoired catchments should be examined. A further 18 reservoired catchments were chosen, the locations of these together with the ten chosen by Macdonald and Scott are shown together in Figure 16. Catchments were chosen to be broadly representative of the population of British dam sites in terms of geographic location, upland and lowland sites, and design storm durations.

Tables 3.2 and 3.3 present the predicted rainfall depths for the 18 extra sites together, for comparison, with those of Macdonald and Scott. The ratios of the 10,000-year estimates by the two methodologies and the ratios of the FEH 10,000-year estimates to those of the FSR PMP estimates, are given in the tables and are shown graphically in Figures 17 and 18. The average regional values of these ratios are summarised in Table 3.1.

Region	Number of estimations	Geometric mean of FEH_{10K}/FSR_{10K} ratios	Geometric mean of FEH_{10K}/PMP ratios
England	19	1.38	1.13
Wales	5	1.38	1.21
Scotland	6	1.43	1.11
Britain	30	1.39	1.14

Table 3.1 Geometric mean ratios of: i) FEH to FSR 10,000-year catchment rainfall depth estimates, and ii) FEH 10,000-year to FSR PMP catchment rainfall depth estimates.

Tables 3.2 and 3.3 also present a revised estimate of the return period of the FSR 10,000-year rainfall depth interpreted in terms of the FEH DDF scale. For clarity these 'revised' levels of risk are presented graphically in Figure 19.

Country	Reservoir	Location number - figure 16	FSR storm duration (h)	FSR 10,000 year (mm)	FSR PMP (mm)	FEH 10,000 year (mm)	Ratio FEH_{10K}/FSR_{10K}	Return period of FSR 10,000 yr rainfall on FEH DDF scale (Years)	Ratio FEH_{10K}/PMP
England	Gorpley	12	3.75	161	187	258	1.60	1776	1.38
England	L. Slade*	23	3.75	156	188	214	1.37	2805	1.14
England	Errwood	14	4.25	145	183	231	1.59	1757	1.26
England	Angram*	10	5.25	191	201	259	1.36	3024	1.29
England	Bicton College	21	5.75	179	212	212	1.18	5032	1.00
England	Olton*	16	5.75	168	205	201	1.2	4924	0.98
England	Stocks*	11	6	184	205	266	1.45	2281	1.30
England	Hayeswater	9	6.13	217	231	272	1.25	3708	1.18
England	Adlington*	13	6.5	161	206	221	1.37	?	1.07
England	Bewl Bridge	20	6.75	166	221	253	1.52	2006	1.14
England	Brent*	19	7.25	164	208	263	1.6	1762	1.26
England	Saddington	15	11	170	237	263	1.55	1700	1.11
England	Ravensthorpe*	17	11.5	182	214	263	1.45	2159	1.23
England	Stocks*	11	12	223	244	316	1.42	2224	1.30
England	Roadford	22	12.5	203	270	238	1.17	4793	0.88
England	Derwent	8	13	192	243	232	1.21	4133	0.95
England	Alton Water	18	17	184	258	279	1.52	1931	1.08
England	Adlington*	13	18.5	197	256	256	1.3	?	1.00
England	Kielder	7	25	220	253	268	1.22	3866	1.06

*Reservoir site used by Macdonald and Scott

Table 3.2 Estimated catchment rainfall depths for summer PMP and both the FEH and FSR 10,000-year design events (England).

Country	Reservoir	Location number - figure 16	FSR storm duration (h)	FSR 10,000 year (mm)	FSR PMP (mm)	FEH 10,000 year (mm)	Ratio FEH_{10K}/FSR_{10K}	Return period of FSR 10,000 yr rainfall on FEH DDF scale (Years)	Ratio FEH_{10K}/PMP
Scotland	Whinhill	3	4.25	137	175	182	1.33	2904	1.04
Scotland	Muirhead	5	6.75	139	203	212	1.53	1414	1.04
Scotland	Afton	6	8.75	190	219	283	1.49	1613	1.29
Scotland	Backwater	2	9.5	144	213	208	1.44	1756	0.98
Scotland	Rowbank	4	9.5	164	204	215	1.31	2702	1.05
Scotland	Glascarnoch	1	11.25	172	194	256	1.49	1646	1.32
Wales	Llyn Crafnant	28	5.25	198	197	320	1.62	1524	1.62
Wales	Egnant*	27	5.25	185	221	262	1.42	2422	1.19
Wales	L Neuadd*	25	5.75	221	224	295	1.33	2956	1.32
Wales	Llysyfran*	24	10.5	204	264	263	1.29	3076	1.00
Wales	Llyn Brianne	26	11.5	224	283	283	1.26	3528	1.00

*Reservoir site used by Macdonald and Scott

Table 3.3 Estimated catchment rainfall depths for summer PMP and both the FEH and FSR 10,000-year design events (Scotland and Wales).

3.2 Discussion

3.2.1 10,000-year estimates

The findings of Macdonald and Scott are sustained in the larger sample set of catchments considered here. The results from the additional 18 catchments are similar in terms of both ratio magnitudes and their range of variability. The average catchment ratios seem to be in broad agreement with the values for the average of the whole of Britain given in Section 2, Table 2.1. Although the Scottish average is slightly higher, little significance can be given to the difference due to the small sample size and the evident variability.

When the return periods of the 10,000-year FSR rain depth estimates are re-evaluated on the FEH DDF scale they dramatically decrease from 10,000 years to return periods of between 1500 and 5000 years. The size of these differences and their associated significance to reservoir design safety will be of concern to Panel Engineers and reservoir owners. It is foreseen that the reservoir community will require additional work that investigates these differences if they are to accept application of the FEH methodology for the purposes of reservoir safety.

3.2.2 Probable Maximum Precipitation

Of the FEH 10,000-year rainfall depths, 22 are estimated to be larger than the PMP depths; 4 are estimated to be lower; and 4 are estimated to be about the same. This study, albeit with a small sample size, suggests that about three-quarters of the FSR PMP values are exceeded by the FEH 10,000-year estimates, and that the exceedence can be as high as 50% or even more. The following paragraphs set these findings in the context of past and possible future PMP derivation studies.

In the UK the PMP is used to derive the Probable Maximum Flood (PMF) which is the recommended design flood for dams in category A (the highest hazard rating) using FRS. The derivation of PMP was included in FSR alongside the derivation of *T*-year rainfall and the values have, in practice, been found to be broadly consistent in that estimates of PMP are generally higher than the 10,000-year rainfalls. This is thought to reflect that the FSR *T*-year rainfall and PMP estimation methods were devised concurrently by an integrated team at the UK Met Office. This mutual compatibility is thought to be a unique attribute of the FSR methods. Statistical and "meteorological maximisation" approaches adopted in other countries tend to have little in common. In consequence, most dam safety procedures worldwide lean either towards a *T*-year approach or a PMP approach, rather than straddling the two approaches as UK practice continues to do.

There is no reason to expect a new, independently produced, rainfall frequency estimation procedure, such as that presented in FEH Volume 2, to provide estimates that sit comfortably with the existing PMP estimates from FSR. This can explain the contradictions found in this study between the FEH 10,000-year rainfalls and the FSR estimates of PMP. The implication is that, if the FEH rainfall frequency assessment estimates are adopted for UK reservoir flood design, there will be immediate concern that these contradict the PMP estimates in many cases.

Several courses of action might then be considered to resolve the contradiction, including possible new research on PMP. However, it should be noted that both areas of research (T-year and PMP estimates) have such different specialisms that it could be difficult to construct a research team that is comfortable with both advancing research in one field, and reconciling it with research in the other.

4 Extent of provisional revisions to "Floods and Reservoir Safety"

This section looks at the areas or sections of the 3rd Edition of Floods and Reservoir Safety (ICE, 1996) that may require amending in light of the issues identified by this project and the findings of the associated recommended work (when completed).

4.1 General

The 3rd Edition of the Institution of Civil Engineers' publication entitled "Floods and Reservoir Safety" (FRS) was published in 1996. That document superseded the previous editions of the Guide, which had been published in 1978 and 1989 respectively. The 3rd Edition of FRS was the outcome of a review that took account of research undertaken up to that time into

- the relationship of PMF to T-year floods
- the dependence of wind and rainfall extremes
- the calculation of wave allowances on reservoirs and the evaluation of wave damage
- snowmelt rates

Since its introduction in 1996, the Guide (3rd Edition FRS) has been used by reservoir owners and Panel Engineers to assess the design flood appropriate to a particular reservoir structure and the ability of the overflow works to pass that design flood.

In the introduction to FRS, it is made clear that the document is intended to be read in conjunction with the latest revisions to the Flood Studies Report (FSR) and associated publications. However, the introduction also notes that Panel Engineers will need to remain abreast of research findings "such as the forthcoming Flood Estimation Handbook ..... and the associated National Rainfall Frequency Study". The need for continual assessment and review is therefore noted within FRS. This section looks at the Guide in more detail and highlights areas or sections of it that may require amending in light of the findings of this project and the findings of this project's recommended work. To ease the understanding of the potential implications, each of the chapters has been reviewed and comments on the potential need for any changes are given under the chapter sections and titles.

4.2 Chapter 1 – Introduction

As stated previously, this makes reference to the FSR being an integral part of the approach to flood assessment. For at least the lower return period floods (150-year & 1000-year) it is likely that the Flood Estimation Handbook (FEH) will be the preferred assessment tool to be used by owners and inspecting engineers in the future.

Amendment to the introduction would, therefore, be required, in order to introduce the use of FEH for flood assessment purposes at reservoirs.

4.3 Chapter 2 – Floods and waves protection standards

There would appear to be few changes required to this particular chapter of FRS as a direct result of FEH. However FEH may be the catalyst that prompts a comprehensive review of the acceptable risks for the various categories of reservoir, as set out in FRS Table 1. Chapter 6 of this report includes a recommendation to this effect.

FRS uses both deterministic and probabilistic methods ie PMF and T-year floods. Any review is likely to consider whether both approaches should continue to be used.

The chapter finishes with a note regarding "Rapid assessment of existing dams". The need for the method would need to be reviewed to see how appropriate it still is if FEH is to be adopted. The rapid method is based around parameters from the Flood Studies Report. Subject to its future appropriateness, it may be that changes would be required to make it more consistent with the assessment method used in FEH.

4.4 Chapter 3 – Derivation of reservoir design flood inflow

This chapter relies heavily on the Flood Studies Report and, in effect, it summarises the FSR method of assessment of design flood inflow. If the FEH is to be recommended for future assessments of reservoir design floods, either in whole or in part, then a revision of this chapter will be required.

Certain sections of the Chapter concern the Probable Maximum Flood (PMF). Until any amendments are made to the methods for derivation of PMF, then these sections will be unchanged.

Comment is also made within the chapter that flood computations may be carried out manually or by using a computer package such as Micro-FSR. CEH Wallingford have expressed the view that they may not continue to support the development of Micro-FSR.

4.5 Chapter 4 – Reservoir flood routing

No amendments are anticipated as being required to this chapter subsequent to the publication of FEH.

4.6 Chapter 5 – Wave surcharge and dam freeboard

No amendments are anticipated as being required to this chapter subsequent to the publication of FEH.

(There would also be an opportunity to update this chapter to make comment on the findings from the pending report on the Impact of Climate Change on Reservoirs.)

4.7 Chapter 6 – Floods during dam construction and dam improvement works

While the basic concepts outlined in this chapter remain sound, it would need updating to include advice on the use of the appropriate FEH methodologies for the estimation of the relatively low return-period floods that the diversion structures should be designed to accommodate.

4.8 Chapter 7 – The overtopping of embankment dams

No amendments are anticipated as being required to this chapter subsequent to the publication of FEH.

4.9 Appendix 1 – Rapid assessment of flood capacity and freeboard at existing dams

This section sets out the methods to be adopted to allow owners and inspecting engineers to assess quickly the likelihood of works being required to address deficiencies in freeboard provision at dams. Much of it is based around the Flood Studies Report and supplementary documents. If the FEH methodology is found to be more appropriate then this will need to be reviewed and a decision taken as to whether the rapid assessment methodology should be refurbished or abandoned.

4.10 Appendix 2 – Detailed advice on applying the FSR to reservoir safety

A wholesale review of this section will be required if it is determined that the use of FEH is more appropriate for T-year return period floods. (The advice contained in the Appendix is based around a broad recommendation to adopt the Micro-FSR program for analysis of reservoir floods).

It is of interest to note that introduction to Appendix 2 highlights the fact that various research programmes are in progress that will have relevance to the estimation of design flood. The ones mentioned are:

- research into joint probabilities
- research by the Meteorological Office: a new PMP model

- IH research to produce a new flood estimation handbook for the UK

These have all been effectively completed and their relevant findings need to be incorporated within the Guide where appropriate.

Considerable elements of the Appendix concern the estimation of Probable Maximum Precipitation (PMP). No changes can be made to this as a result of FEH, although the implications of the FEH (as it stands) are that further research work may be required to determine if the PMP estimates which are currently being used and which are embodied in FSR are appropriate.

The sections on "Catchment representation" and "Design storm" will need to be reviewed as part of an overall assessment of the document if FEH is adopted. The section on "Reservoirs in cascade" is probably still appropriate and is unlikely to require major modification. Similarly, the section on "Local data" will probably still be appropriate, although it does refer to the FSR procedure throughout. In "Other factors", there is unlikely to be significant changes to the text although again it refers to FSR throughout. The section on "Linking the flood frequency curve to the PMF estimate" will need to be assessed in detail in view of the fact that the FEH appears to be giving results for the 10,000-year return period flood which are close to or in excess of those determined by FSR for the PMF.

4.11 Glossary

This will need to be reviewed if the FEH approach is to be adopted for reservoir flood studies.

4.12 Key references and bibliography

This will need to be reviewed if the FEH approach is to be adopted for reservoir flood studies.

4.13 Means of undertaking revisions

The 3rd Edition of Floods and Reservoir Safety was produced by a technical contractor working under the guidance of a working party set up by the Institution of Civil Engineers. Funding for the review was obtained from the Department of the Environment (and relied heavily on unfunded contributions – not least in technical writing).

It can be seen from the previous sections, if the FEH approach is to be adopted, that comprehensive review of FRS will be required. If this is necessary it is recommended that a similar approach be taken to that adopted for the 3rd Edition, namely a technical contractor working under the guidance of a working party. However any contribution considered necessary from other organisations should also be appropriately funded. In view of the importance of this topic to reservoir safety in the U.K., it is recommended that if the findings of the recommended work (Section 6) confirm that revision of the FRS is necessary then the Department of the Environment, Transport and the Regions (DETR) give consideration to funding the production of the 4th Edition. Membership of the working party should be drawn from hydrological experts, panel engineers, owners, and representatives of central government.

The programme and timescale for any required review will of course be dependent on the outcome of various other topics that are recommended in this report. It is suggested that the need for, and composition of, any working group be deferred until the findings of the recommended research are known. However the issues are of such importance it is urged that the recommended research (Section 6) be carried out as soon as possible so that the concerns of the reservoir community can be rapidly addressed and the need (or not) for a wholesale review of the FRS established. A realistic timescale must be set to meet the demands of both further research and of the urgent need to clarify the situation that owners and panel engineers now find themselves in.

5 Interim guidance for Panel Engineers

The recommendation of this project is that further study is required before clear guidance can be given to owners and panel engineers on the way forward for the assessment of reservoir flood safety. Any guidance that can be issued at this stage must therefore be regarded as interim in the light of the further research recommended (Section 6).

It is recommended that DETR consider issuing interim guidance to all panel engineers to allow them to understand the issues that are being looked at and the reasons why FEH is giving significantly higher T-year return period rainfall than that assessed by FSR. This could take the form of a guidance note based on the information contained in this report or, alternatively, issue of the report itself to all AR Panel Engineers. For the benefit of owners and in the interests of public safety, it is important that in this interim stage, panel engineers try to adopt a fairly uniform stance in respect of the way they deal with flood risk at reservoirs. Any guidance issued should try to achieve this and in this respect the following points are ones that are considered of relevance.

Three circumstances need to be considered:

1. Works recommended, but not yet carried out.
2. New reservoirs.
3. Flood assessments under review.

5.1 Possible options

In the interim the owners and the reservoir Panel Engineers have a number of options open to them and it will depend upon the circumstances of each reservoir which option is appropriate:

Option 1 – if a delay is considered practicable postpone the works pending the publication of more definitive guidance based upon the findings of the recommended research.

Option 2 – if a delay is not practicable and a two-stage approach is technically feasible and is financially and environmentally acceptable,
Stage 1 – increase the spillway capacity using the FSR design rainfall.
Stage 2 – further increase the capacity if and when a higher design capacity is recommended.

Option 3 – if a delay is not practicable and a two-stage construction is not technically feasible or financially or environmentally acceptable, increase the capacity using the FEH design rainfall, or in the case of PMF use the worst case from FSR PMP and FEH 10,000 year. However it should be recognised that i) this does not discount the possibility that spillway capacities may still need to be increased if a new PMP methodology is developed that gives rises to higher PMFs, and ii) it is possible that further measures will be required depending upon the findings of further work.

In circulating this interim guidance it will be important that the expected publication date of the findings of the recommended research be clearly indicated, so that Panel Engineers and owners can properly assess the options. However it should be noted that the timetable will be, to some extent, influenced by the findings of the actions recommended in Section 6.

If a dam could tolerate overtopping, Table 1 of FRS recommends that the overflow should pass the "minimum" standard reservoir design inflow flood safely. For Category A dams, the "normal" standard inflow flood is the Probable Maximum Flood (PMF). The FEH does not alter the FSR PMP estimates A dams. However, if a Category A dam could tolerate overtopping (or could be made to tolerate overtopping, for example by reinforcing the grass on the crest and downstream slopes[4]), the "minimum" 10,000-year flood applies, and could be estimated from FEH. The design inflow floods for Category B, C and D dams are 10,000, 1000 and 150 years respectively, and FEH could also be applied.

5.2 General points

The wording in the Reservoirs Act 1975 concerning measures in the interests of safety states that these should be undertaken by the undertakers "as soon as is practicable". Panel Engineers can give their views on what they believe to be "practicable" and, in this interim stage, they will wish to consider the programme and timescale that the DETR choose.

Reservoir safety in the UK is the responsibility of reservoir owners, the individual panel engineers, and the enforcement authorities. It is important to highlight in any note issued by DETR that these responsibilities are not changed by the issue of guidance in response to FEH. However, most Panel Engineers will regard guidance such as that set out in this section as being the current best practice until more detailed information is available. It is important, however, that they make the owners and undertakers fully aware of the situation, discuss the risks in delaying works with them, and reach agreement on the interim way forward. It may be that while a Panel Engineer is prepared to accept that action be deferred until more detailed guidance is available, the owner/undertaker may decide that the risk to his business and his reputation in the event of failure due to actual or potential under-provision of spillway capacity is such that he is prepared to proceed with works even though - a) these may require further modification in the foreseeable future, or b) be judged as over-conservative in due course.

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[4] refer to CIRIA Report 116 (Hewlett et al., 1987).

It would be appropriate to advise panel engineers of any further studies that are initiated in order that they are fully conversant with the situation and the likely timescales for completion of any additional research.

6 Technical recommendations

The aim of the project was to clarify by how much the FEH and FSR rainfall estimates differed; to provide a rationale for any differences; and to then provide the DETR with guidance as to what the implications for the 3rd Edition of "Floods and Reservoir Safety" might be, and whether useful interim guidance based upon this initial study could be proposed. The project was not set up to perform a detailed technical review of the FEH methodology, but rather to act as a scoping study to clarify what the present position is regarding the FEH rainfall in the context of reservoir safety. The following technical recommendations are therefore mainly recommended to provide improved confidence in the FEH methodology. They should provide Government with a better-informed platform from which to make a critical assessment of the use of the FEH rainfall method in reservoir flood studies.

6.1 Revision of the DDF parameters c and E

The evidence of parameter interaction in the DDF model should be investigated further and remedied.

An unexpected feature has been detected in the way that the FEH rainfall depth-duration-frequency model (DDF) has been fitted. There is evidence of interaction between two of the model parameters (c and E). Although this will influence the final rainfall estimates obtained by users, the effects may be relatively minor when the model is applied within its return-period range of calibration (2 to 1000 years). However given that reservoir safety applications require extrapolation to 10,000-year estimates, it is recommended that the parameter-interaction should be investigated further and remedied.

CEH may undertake this investigation as part of its support to users of the FEH.

6.2 Validation of the FEH design rainfall estimates

Each of the component parts of the model (RMED, FORGEX, DDF) has been separately assessed to some extent. For example Section 8.7 of FEH Volume 2 briefly describes an assessment of the performance of FORGEX. However these component assessments, although encouraging, do not form a final validation of the whole integrated model. Because of spatial-dependence effects, such validation is not straightforward. But it is required if reservoir safety users are to gain confidence in the FEH design rainfall estimates.

It may not be possible to securely validate the methods at the long return periods most relevant to reservoir flood safety assessments. However, validation of the FEH method (and, in consequence, refutation of the FSR method) in the return period range 50 to 500 years would strengthen the case for accepting the new method at all return periods. The approach recommended is to count the number of very rare events observed by UK raingauge networks. This will not be without some difficulty. As Dales and Reed (1989) demonstrate, the effect of spatial dependence in extreme rainfalls is to lead to clustering of such exceedances in time. It will therefore be necessary to adopt a counting system that takes due account of spatial dependence and the irregular density of UK raingauge networks.

Inclusion of the corresponding Flood Studies Report design rainfall estimates within the validation exercise is recommended and would benefit the comparison of the two methodologies.

6.3 Research into the extrapolation methodology

The FEH development team's remit was to develop an improved means of estimating design events up to an upper threshold of 2000 years. Consequently limited effort was focused upon the difficult issue of how best to extrapolate to the very long return periods. The FEH DDF model, as it stands, imposes a log-Gumbel functional form on the relationship between rainfall depth and return period. This is recognised (Section 2.3.2) as an issue that would benefit from more detailed, targeted work.

6.4 More UK rainfall records be brought into digital form

The patterns of the DDF model parameters – particularly parameter E – show other effects that are less than ideal. These arise from peculiarities of the gauge networks used in the FEH Volume 2 research. Specifically, the concentration of long-term gauge records in central London has led to "boundary effects" at a distance of 200 km: the maximum radius at which data are pooled in the FORGEX method. Altering the FORGEX method to suppress this is not recommended. It is suggested that the feature is a useful reminder that the quality of estimates by FORGEX (and other methods) is strongly dependent on the extent of data records available. Put another way, the arced feature in central England evident in parameter E (Figure 14) would not be there if more (and longer) rainfall records evenly distributed across Britain had been available to the Volume 2 research. Such further records exist (notably in the national archive at the Met. Office) but have yet to be computerised. It is therefore recommended that Government considers the case for many more UK rainfall records to be brought into digital form.

6.5 Issues surrounding PMP

The project has identified the potential for inconsistencies between PMP and 10,000-year rainfall estimates. These may need to be reconciled. Given the importance of PMP within the British reservoir flood assessment approach, it is recommended that careful consideration be given to the reassessment of current PMP methodology. In this regard the following tasks are suggested if re-examination of PMP estimates are deemed necessary:

1. Revise, or gain more confidence in, the 10,000-year estimates.
2. Revise UK PMP estimates.
3. Reconcile the 10,000-year and the PMP estimates.

6.6 Overall risk assessment strategy

At present the risks associated with extreme floods are considered without formal reference to the risks associated with other aspects of reservoir safety, such as the potential for instability and internal erosion. It is not appropriate in a brief report such as this to consider the implications of attempting to devise an overall risk assessment strategy in which floods form an element. However such a strategy would require consideration of whether the T-year approach should become the norm for flood risks with PMF falling into disuse. As a preliminary step it is recommended that consideration is given to the benefits and disadvantages of attempting to devise an overall risk assessment strategy in which flood estimation is one element. It is likely that the imminent CIRIA guide on risks and reservoirs (CIRIA, 2000) would be of value to this suggested review.

6.7 Urgency

The apparent differences in estimated design rainfall depth are highly significant to reservoir owners and Panel Engineers in terms of both safety and potential expenditure. It is therefore suggested that these recommendations be given urgent consideration so that definitive guidance can be issued at the earliest possible opportunity.

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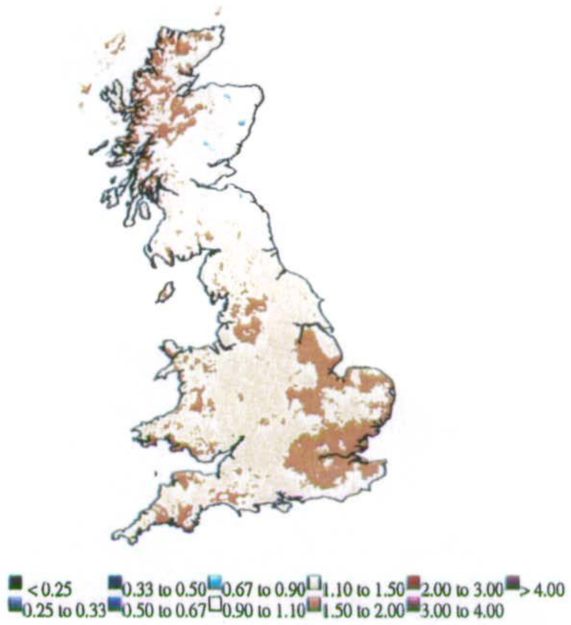
8 Glossary

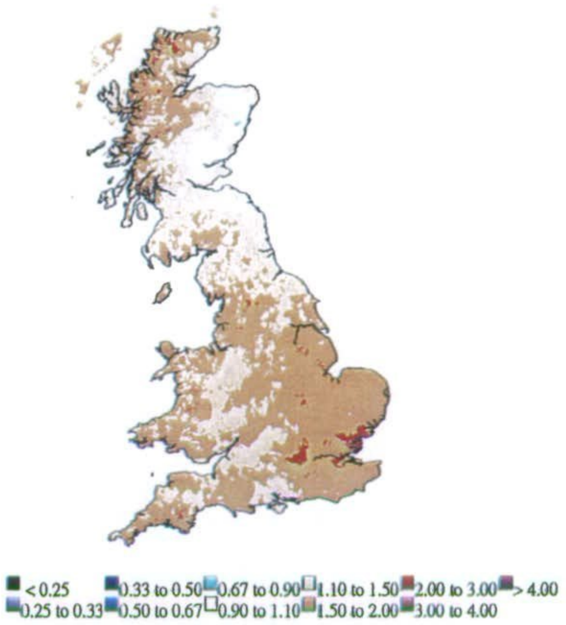
DDF	Depth-Duration-Frequency. DDF models or tables describe the design characteristics of extreme rainfall events at a specific location or over a region in terms of the depth of storm rainfall, the duration of the rainfall, and the rarity of the event.
FORGEX	FOcused Rainfall Growth curve Extension method It establishes a relationship between the relative magnitudes of storm events with differing rarities at a specific location. The method is applied to a 1-km grid covering the whole of the UK. The resulting grids of growth rates are used to multiply the corresponding grids of RMED to give design rainfalls.
Geometric Mean	The geometric mean, rather than the arithmetic mean, is appropriate when averaging ratios. The geometric mean, GM, of N values, $(x_1, x_2, \ldots x_N)$, is given by: $\ln GM = (\ln x_1 + \ln x_2 + \ldots \ln x_N)/N$
Growth curve	The curve is used to multiply the index rainfall depth (RMED) to estimate the rainfall depths of rarer events.
PMF	The flood hydrograph resulting from PMP and, where applicable, snowmelt coupled with the worst flood producing catchment conditions that can be realistically expected in the prevailing meteorological conditions.
PMP	The (theoretical) greatest depth of precipitation for a given duration meteorologically possible for a given basin at a particular time of year. It includes rain, sleet, snow and hail as it occurs, but not snow cover left from previous storms.
RMED	Median annual maximum rainfall (mm). This is the index variable for the FEH DDF model from which design storm depths of user specified duration and rarity are calculated. Values of RMED have been interpolated between raingauge sites using topographic information, giving 1-km grids of RMED covering the UK.
d_1, d_2, d_3, c, E, f	The six parameters that completely define the DDF model. (Refer to section 2.4.1 of this report for a brief description, or FEH Vol 2 for a fuller description of the model)



Ratio of FEH/FSR rainfall depth for

T = 193, d = 1 hour

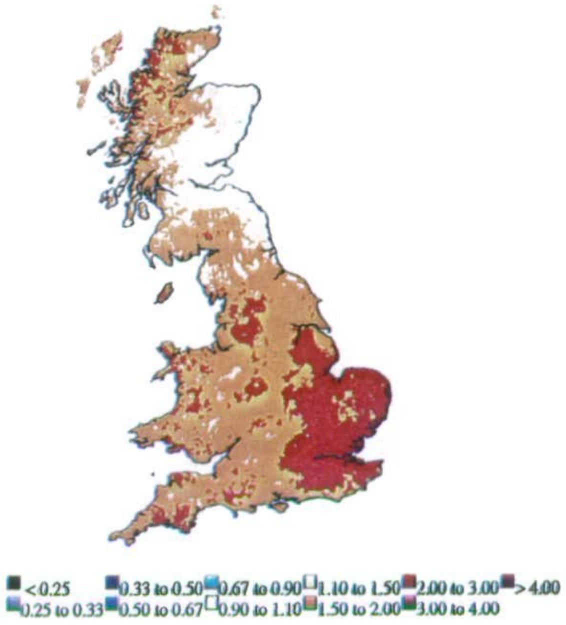
Figure 1



Ratio of FEH/FSR rainfall depth for

T = 1000, d = 1 hour

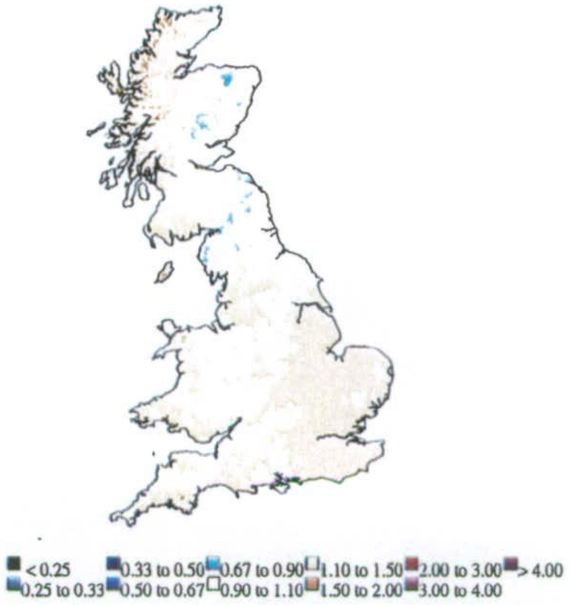
Figure 2



Ratio of FEH/FSR rainfall depth for

T = 10000, d = 1 hour

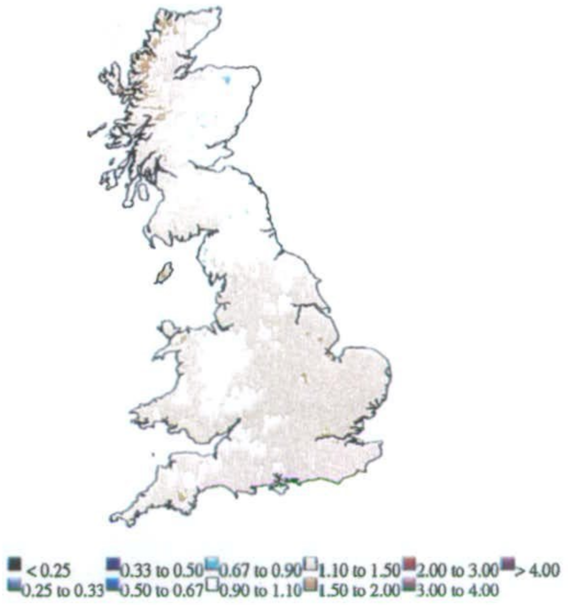
Figure 3



Ratio of FEH/FSR rainfall depth for

T = 193, d = 6 hour

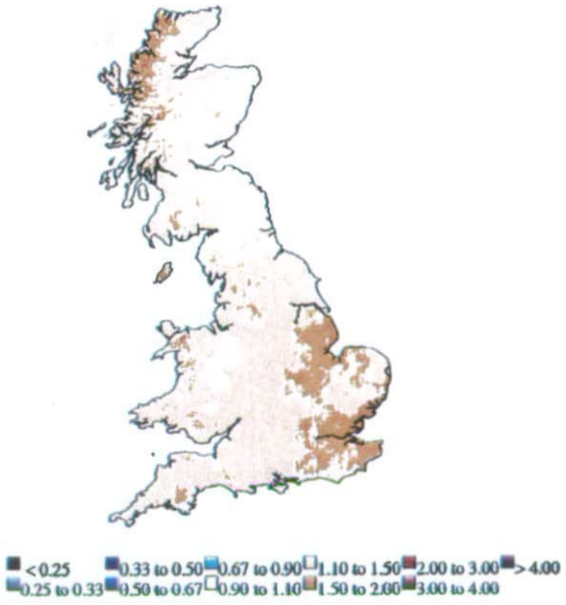
Figure 4



Ratio of FEH/FSR rainfall depth for

T = 1000, d = 6 hour

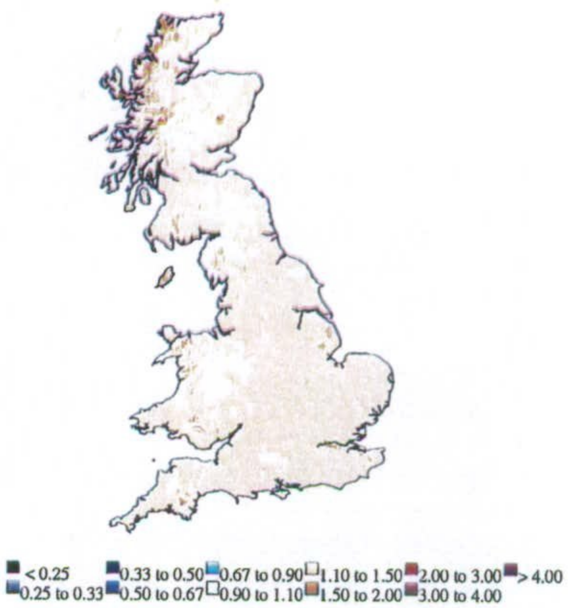
Figure 5



Ratio of FEH/FSR rainfall depth for

T = 10000, d = 6 hour

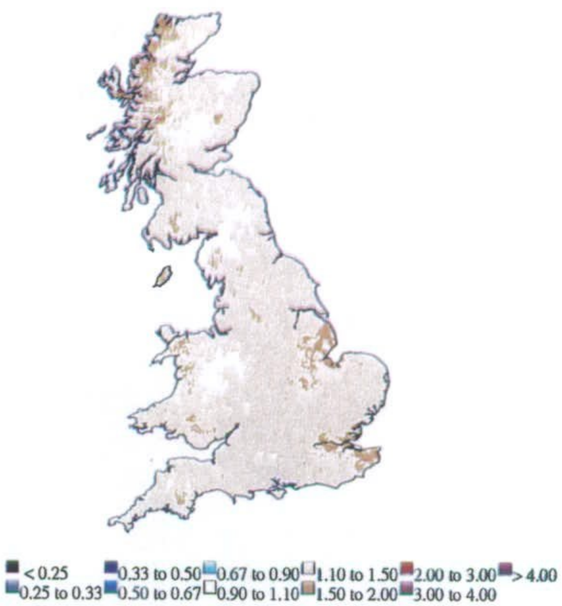
Figure 6



Ratio of FEH/FSR rainfall depth for

T = 193, d = 1 day

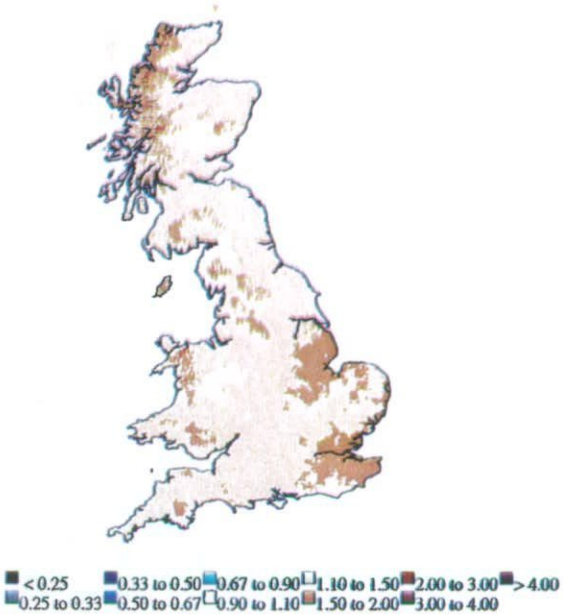
Figure 7



Ratio of FEH/FSR rainfall depth for

T = 1000, d = 1 day

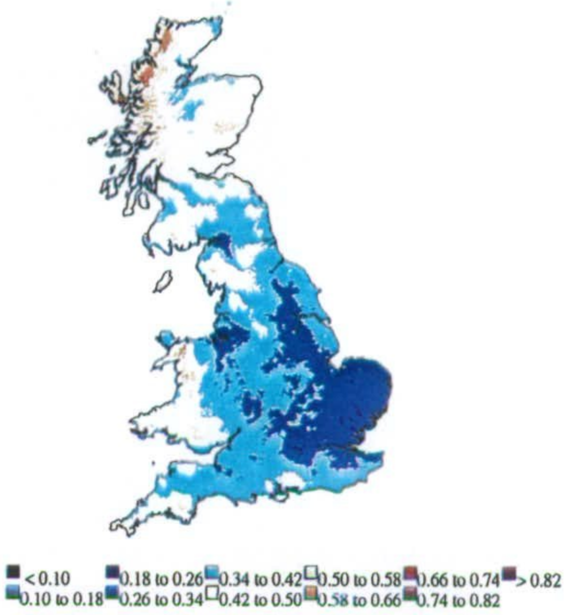
Figure 8



Ratio of FEH/FSR rainfall depth for

T = 10000, d = 1 day

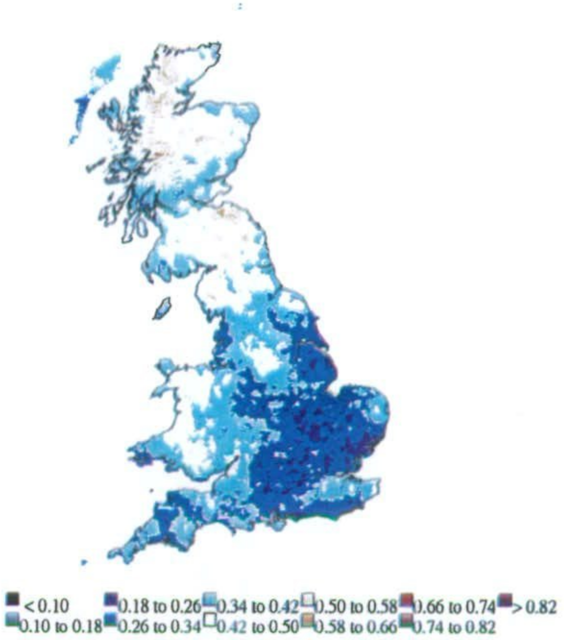
Figure 9



Depth duration frequency model

Parameter d1

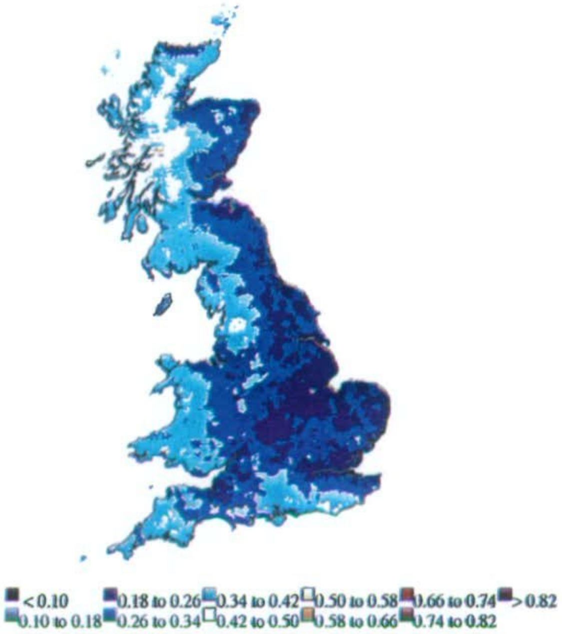
Figure 10



Depth duration frequency model

Parameter d2

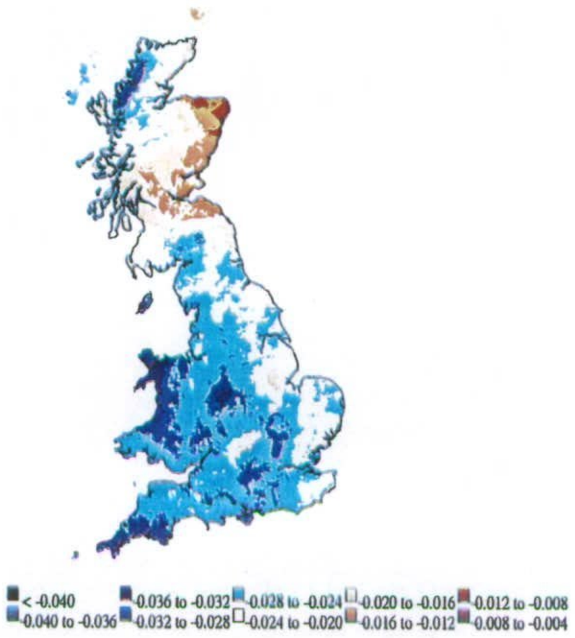
Figure 11



Depth duration frequency model

Parameter d3

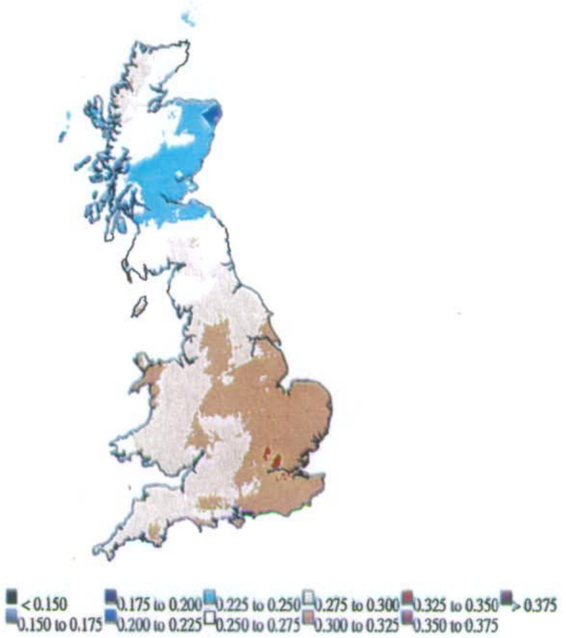
Figure 12



Depth duration frequency model

Parameter c

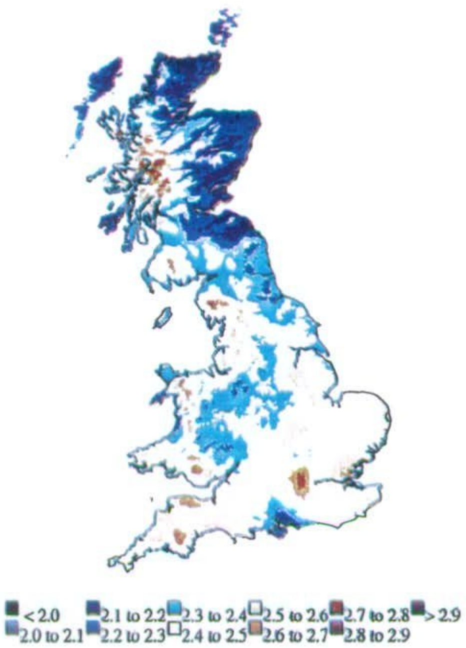
Figure 13



Depth duration frequency model

Parameter E

Figure 14



Depth duration frequency model

Parameter f

Figure 15

Location of the studied reservoirs

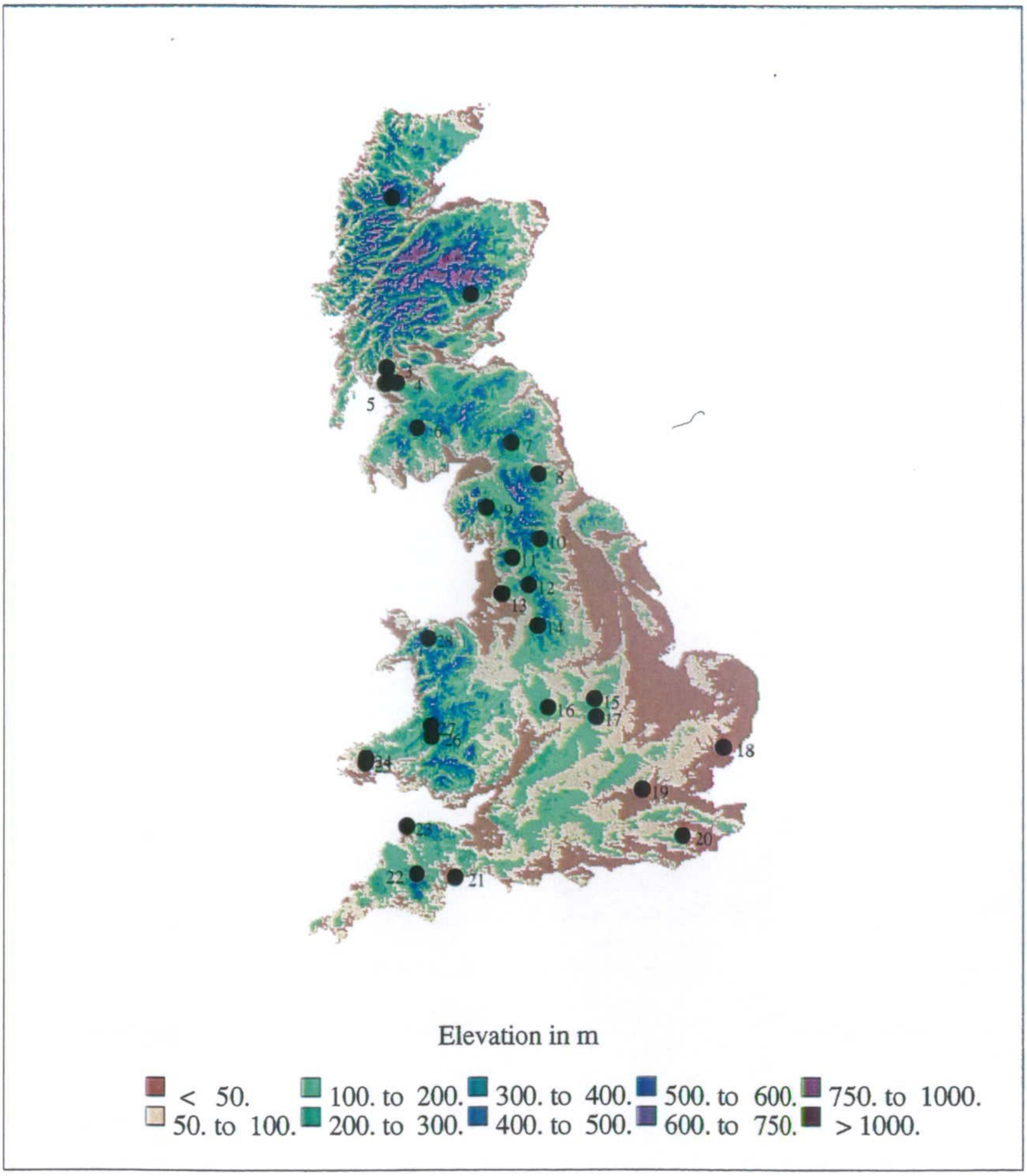


Figure 16 Location of example reservoired catchments

Key to Figure 16

Map Number	**Reservoir**
1	Glascarnoch
2	Backwater
3	Whinhill
4	Rowbank
5	Muirhead
6	Afton
7	Kielder
8	Derwent
9	Hayeswater
10	Angram
11	Stocks
12	Gorpley
13	Adlington
14	Errwood
15	Saddington
16	Olton
17	Ravensthorpe
18	Alton Water
19	Brent
20	Bewl Bridge
21	Bicton College
22	Roadford
23	L. Slade
24	Llysyfran
25	L. Neuadd
26	Llyn Brianne
27	Egnant
28	Llyn Crafnant

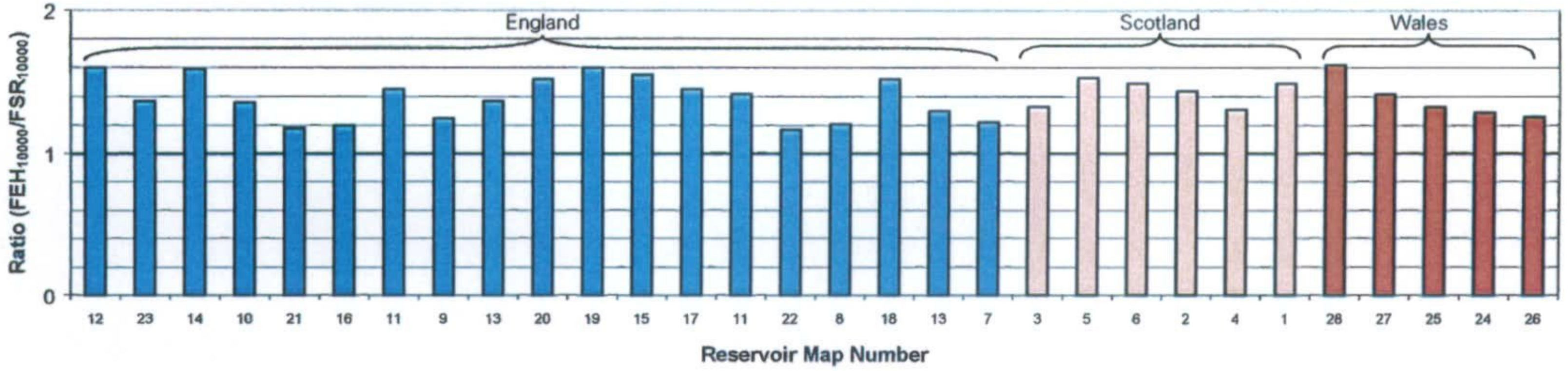


Figure 17 Ratio of FEH and FSR 10000-year estimates of catchment rainfall depths. (Catchments arranged by ascending storm duration)

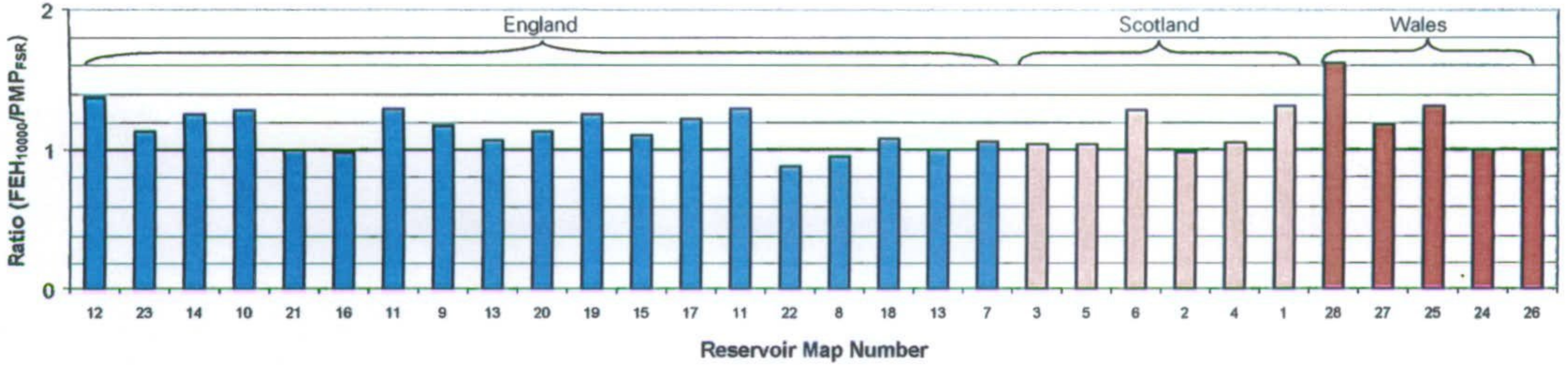


Figure 18 Ratio of FEH 10000-year to FSR PMP estimates of catchment rainfall depths. (Catchments arranged by ascending storm duration)

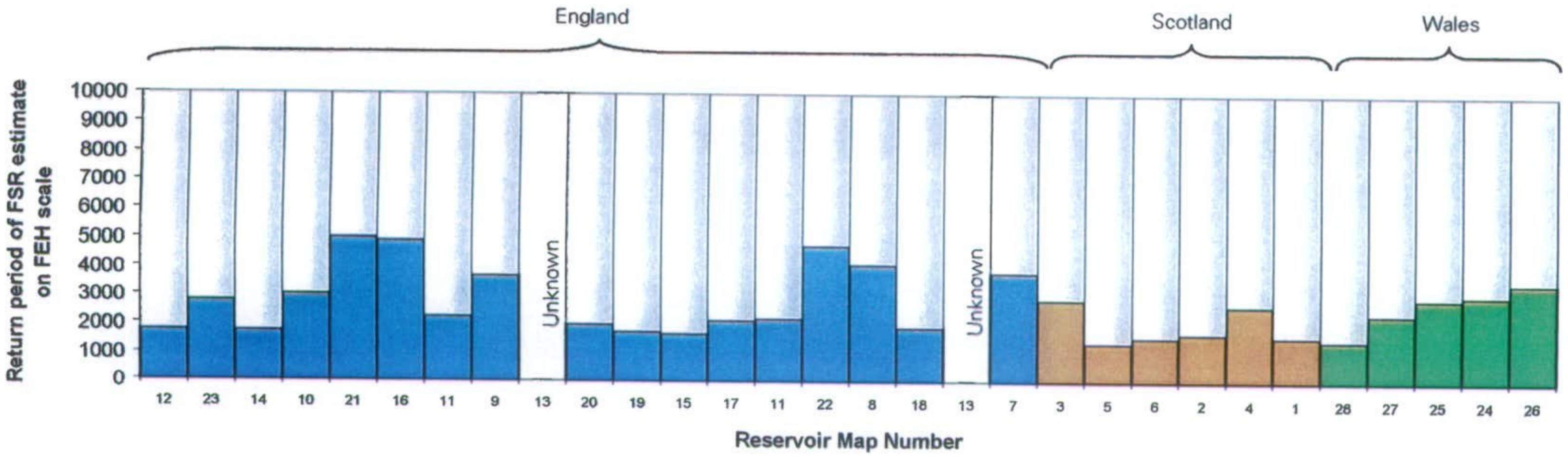


Figure 19 The return period of the FSR estimated 10000-year rainfall depths on the FEH ddf scale. (Catchments arranged by ascending storm duration).