Reservoir safety – long return period rainfall

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SYNOPSIS. Recent research funded by Defra has developed a new statistical model of point rainfall depth-duration-frequency (DDF) for the UK, to replace the current Flood Estimation Handbook (FEH) DDF model. The project was commissioned in response to concerns expressed by reservoir engineers about the apparently high estimates produced by the FEH DDF model when it was applied to return periods in excess of its recommended upper limit of 1,000 years. Within the project, the framework of the FEH model has been retained, but each of its components has been substantially revised and the dataset of annual maxima rainfalls to which the model is fitted has been updated. Comparisons with the FEH model show that rainfall estimates from the new model are generally lower for a given return period, except for shorter durations in Scotland. Further work to develop a new software implementation to allow the model to be applied at any location in the UK is planned for 2010.

INTRODUCTION

This paper gives details of a Defra-funded research project which has developed a revised model of rainfall depth-duration-frequency (DDF) applicable to the whole of the UK. The model has been developed for rainfall durations from 1 hour to 8 days. Although it was originally envisaged that the revised model would be applicable to the long return periods (from 100 to 10,000 years) which are typically used in hydrological analyses for reservoir flood risk assessment, it has been developed for return periods ranging from 2 to over 10,000 years. Therefore, it is proposed that the revised DDF model should eventually replace that published in Volume 2 of the Flood Estimation Handbook (FEH) (Faulkner, 1999) for hydrological design studies using rainfall-runoff techniques and for assessing the rarity of particular rainfall events in the UK.

MANAGING DAMS: CHALLENGES IN A TIME OF CHANGE

Background to the project

Current guidance on floods and reservoir safety (ICE, 1996) divides dams into four categories in terms of the potential hazard to life and property downstream. Greater security is required against dam failure where there is a severe threat of loss of life and extensive damage than where the threat is lower. Therefore, the design standards for dams of category A to D range from the probable maximum flood (PMF) to the 150-year return period flood, respectively. The assessment of reservoir safety requires a complete design inflow hydrograph which is derived from a rainfall-runoff method, in which an appropriate design storm and associated antecedent conditions are applied to a hydrological model of the catchment (NERC, 1975; Reed & Field, 1992; Institute of Hydrology, 1999). In the case of the FSR/FEH rainfall-runoff method (Houghton-Carr, 1999), the appropriate design storm ranges from the 193-year rainfall (used in the synthesis of the 150-year flood) to the probable maximum precipitation (PMP), which is used to generate the PMF. The storm duration critical to reservoir safety varies from a few hours to several days, reflecting the wide range of catchment areas of UK reservoirs, which vary from less than one square kilometre to hundreds of square kilometres.

The FEH and rainfall frequency estimation

Until the publication of the FEH in 1999, UK practice in flood estimation was based on the methods outlined in the Flood Studies Report (FSR) published by NERC (1975) and refined in a number of supplementary reports over the subsequent decade. The FEH (Institute of Hydrology, 1999) introduced a new set of procedures for the estimation of rainfall and flood frequency in the UK. Two particularly innovative features of the FEH synthesis were the use of digital catchment information to aid estimation at ungauged sites, and the introduction of flexible regionalisation schemes. The latter allow the extent of data pooling to be tailored to the target return period. The FEH methods have been widely adopted for a variety of applications including the design and appraisal of flood defence works and the mapping of flood risk. However, the FEH rainfall depth-duration-frequency (DDF) model was developed for return periods of up to 2,000 years and, within the reservoir profession, concern has been voiced about the results it produces for high return periods relevant to the assessment of reservoir flood safety. In some cases (for example, MacDonald & Scott, 2001) it has been noted that the FEH 10,000-year return period rainfall exceeds the estimate of PMP derived from the FSR.

As a result of this problem, and pending the outcome of the research described here, Defra issued interim guidance to reservoir engineers which recommended that the FSR rather than the FEH should be used for the assessment of 1 in 10,000-year return period rainfall. Thus the aim of the project was to re-evaluate the FEH DDF model for return periods above 100 years.

DATA USED IN THE ANALYSIS

The revised model has been developed using an extensive dataset of annual maximum rainfall depths from raingauges across the UK. The study was able to benefit from both the increased record length and the generally higher density of recording raingauges since the FEH analysis was undertaken in the mid 1990s. Annual maxima were abstracted for 11 key rainfall durations ranging from 1 hour to 8 days. Data were available for over 6,500 daily raingauges, providing very good coverage of the UK and representing a slight increase over the number used in the FEH, and for 969 hourly gauges, which is a twofold increase over the FEH. Gauge records were included in the analysis if they were able to provide at least nine annual maximum values. The network of hourly gauges used in the analysis is shown in Figure 1. This indicates that the density of the hourly network is generally good, although there is a noticeable lack of information in the south-west of England, in parts of the south coast region and in Kent. In addition, upland areas are not particularly well represented, although in Scotland, the density of hourly gauges is considerably greater than that available at the time of the FEH analysis. It should be noted that, while networks of recording raingauges do sometimes exist in the areas shown as sparsely gauged in Figure 1, the record lengths are often too short to fulfil the 9-year criterion. This in turn implies that updating the dataset of hourly maxima would be a worthwhile exercise in the future.

Where possible, seasonal maxima were abstracted from continuous records and were analysed in the early stages of the project. The revised DDF model has not been explicitly developed to provide seasonal rainfall estimates, but sets of seasonal correction factors have been derived for application to all-year estimates. Seasonal design values are required for some uses of the ReFH method of hydrological analysis (Kjeldsen, 2007).

Another source of information available to the project was a database detailing 63 extreme storm events experienced in the UK between 1880 and 2006. The original archive consisting of 50 storm events had been compiled by Collier *et al.* (2002), and it was extended and updated by the Met Office within the current project (Dempsey & Dent, 2009). The dataset has been used as a ‘reality check’ against which the final results of the revised DDF model have been compared.

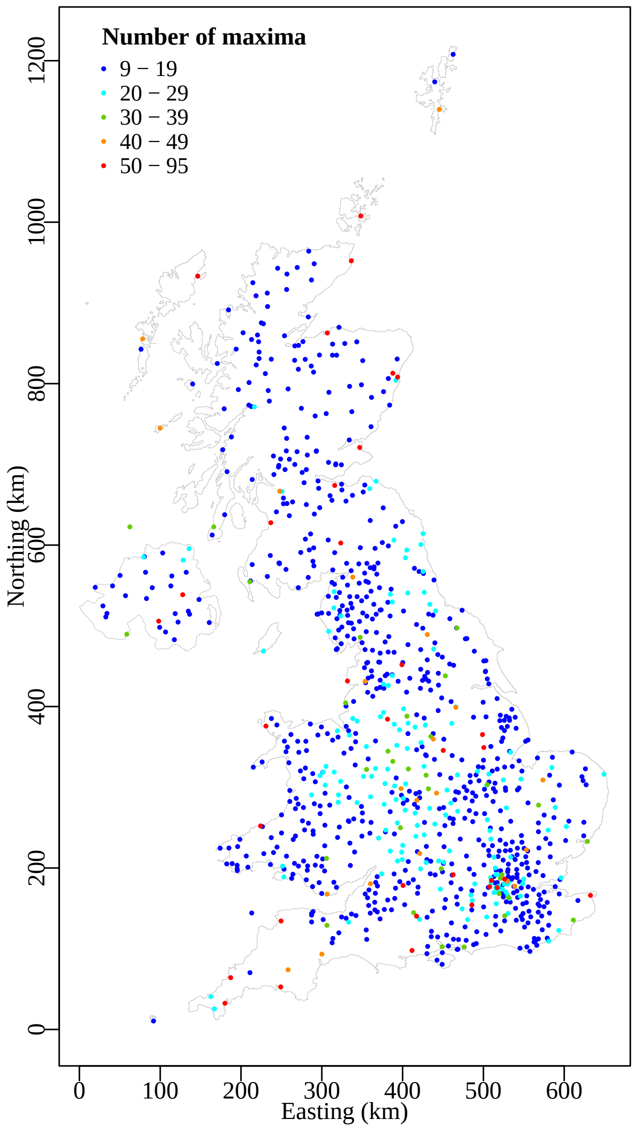

Figure 1. Locations of hourly raingauges with at least nine 1-hour annual maxima

METHODOLOGY

Volume 2 of the FEH (Faulkner, 1999) introduced the Focused Rainfall Growth Curve Extension (FORGEX) method of rainfall frequency estimation. FORGEX adopts the index flood approach, whereby estimates of the variable under consideration are derived as the product of an index variable (in this case, the median annual maximum value of the relevant duration, or RMED) and a growth factor giving the ratio of the T-year value to that of the index variable. Focusing the growth curve on a particular site of interest allows the incorporation of rainfall extremes observed regionally, while also respecting local variations in growth factors. The method pools data from a succession of circular regions centred on the focal point. Following the application of FORGEX across the UK, a DDF model was fitted to the resulting rainfall estimates to allow consistent estimation for any location over a wide range of durations and return periods.

During the project, a number of improvements were made to the FEH FORGEX method and these are discussed briefly in turn.

<u>Revised standardisation</u>

The simple standardisation applied in the FEH, whereby annual maxima at each raingauge are divided by the at-site median value of the appropriate duration (RMED), has been replaced with a revised standardisation expressed by:

$$R_{revised} = 1 + \frac{R - RMED}{f \times RMED} = 1 + \frac{1}{f}\left(R_{standardised} - 1\right)$$

where f is a standardisation factor which varies from site to site and which is derived from known quantities, and $R_{standardised}$ is rainfall standardised by the FEH method. The effect of the revised standardisation is to remove more of the location-dependent variation in rainfall before combining maxima from networks of raingauges.

<u>Revised model of spatial dependence</u>

A new model of spatial dependence in rainfall extremes has been developed within this project and has been incorporated into the revised FORGEX procedure. It allows the degree of dependence within a given raingauge network to reduce (i.e. to tend towards *independence*) at very high return periods. The new model is used within the FORGEX procedure to determine the plotting positions of the highest annual maxima across a network of gauges. Its effect is almost always to shift rainfall frequency curves to the right compared to the FEH model, which increases the return period of a given rainfall depth.

<u>Growth curve fitting</u>

The project has made a number of modifications to the FORGEX method of deriving rainfall growth curves. In particular, these revisions produce curves that are a better fit to the data, and give a more gradual variation between locations.

DDF model fitting

The key output of the current project has been the specification of a revised DDF model. The model is based on a generalised mixture of Gamma distributions in which the scale and shape parameters vary smoothly with duration. The new model is more flexible than the FEH model and is better able to represent the output from FORGEX across the full range of durations and return periods. Unlike the FEH model, the new modelled rainfall does not increase exponentially if extrapolated beyond the range of return periods represented in the observed datasets.

RESULTS AND COMPARISONS

The combined effect of all of the changes to FORGEX is to lower the rainfall frequency curve in almost all cases. An example is given in Figure 2, which shows frequency curves derived from the FEH and revised FORGEX methods for the 24-hour duration focused on the raingauge at Seathwaite Farm, where a new UK record of 316.4mm was recorded on 20 November 2009. It should be noted that this reading was not included in the annual maximum dataset used in the analysis. It can be seen that the revised FORGEX curve plots to the right of the curve derived from the FEH method; both methods have been applied to the same data. This is largely due to the effect of the revised spatial dependence model as discussed above.

Following the revised FORGEX analysis at each site of interest, the next stage of the analysis is to fit the DDF model to the rainfall frequency curves to provide estimates that are consistent across different durations. The tendency for the frequency curves derived from the revised method to be shifted to the right relative to the FEH method means that, in most cases, there is a general tendency for the resulting design rainfall estimates to be lower than those derived from the FEH model for a given return period. However, it is important to note that these effects can be secondary to the effects of the improvements to the underlying dataset in some cases.

The project has compared rainfall frequency estimates from the new DDF model with those derived from the published FEH and FSR models, and also with estimates of PMP calculated using the FSR method. Currently, the revised DDF model can only be applied at locations where reliable estimates of the index variable, RMED, are available for each of the 11 key durations, which means in practice that relatively long hourly and daily raingauge records of acceptable quality are required at each site of interest. A full UK-wide implementation of the model is planned for the coming year and this second phase analysis will include the production of maps of RMED.

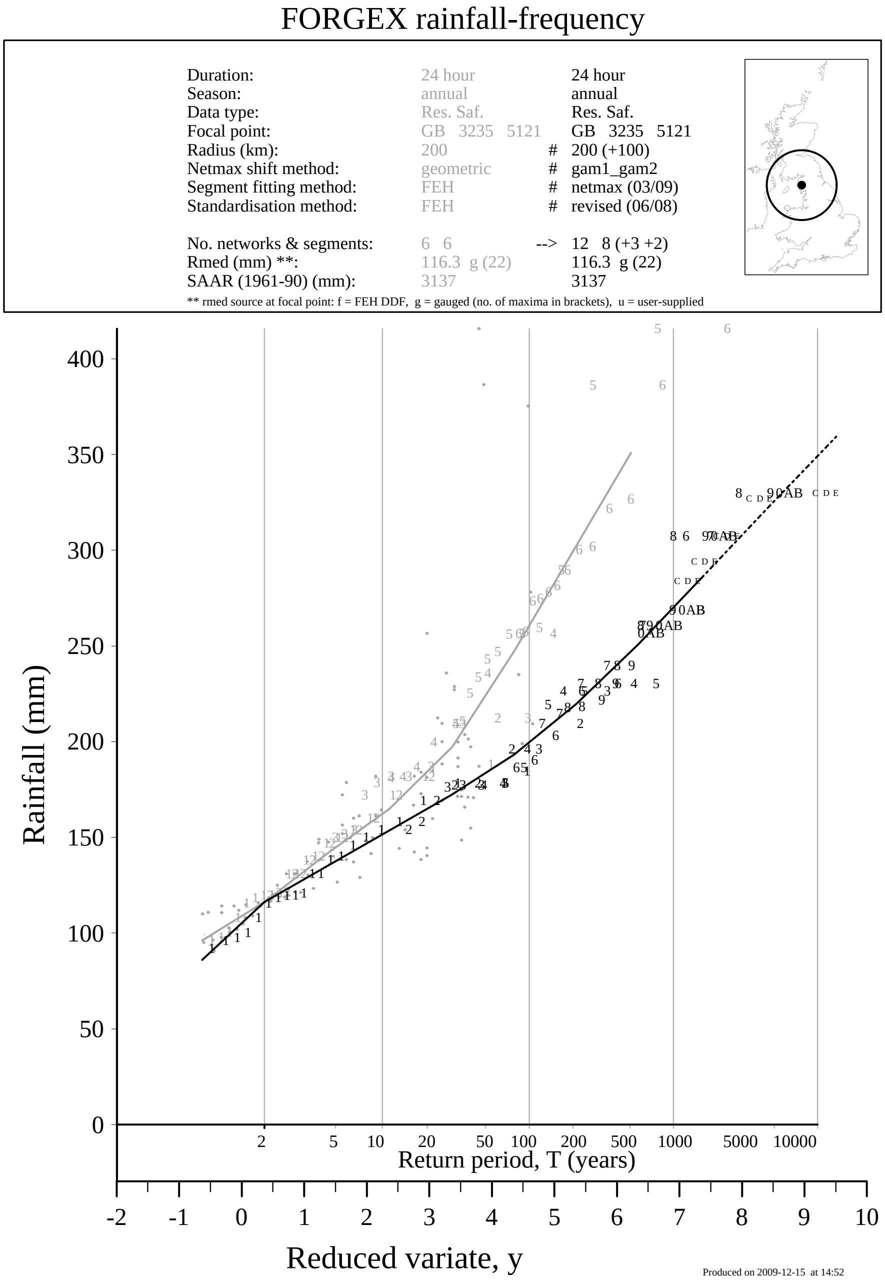

Figure 2. Rainfall frequency curves for the 24-hour duration at Seathwaite Farm, Cumbria derived from FEH FORGEX (lighter line) and revised FORGEX (darker line) methodologies.

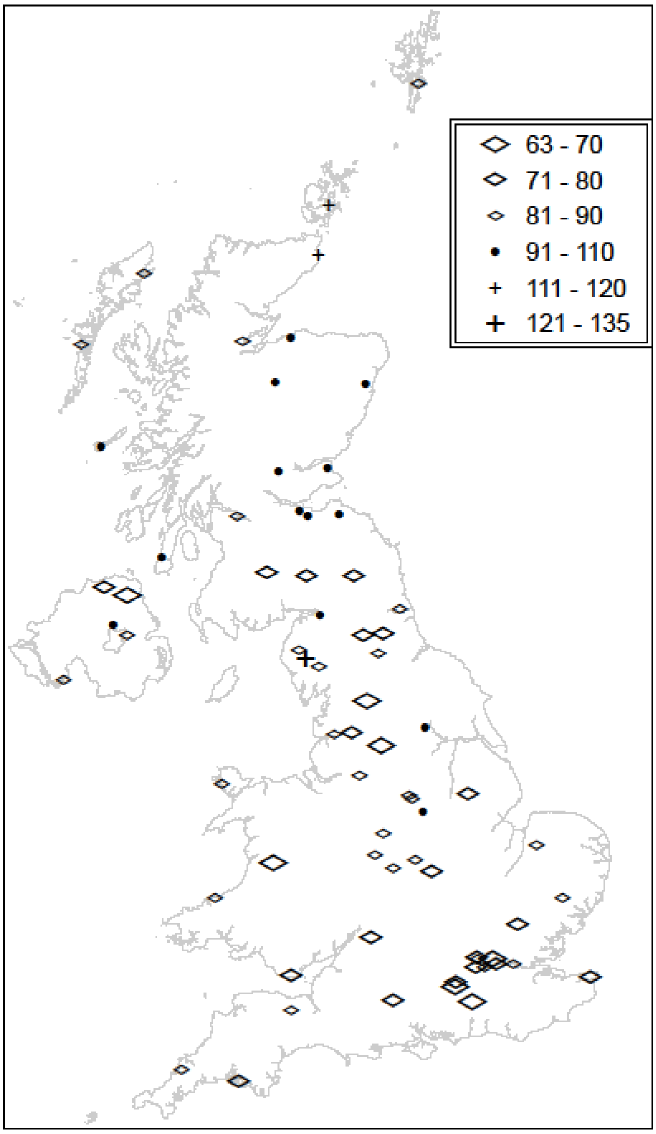

Figure 3. New rainfall estimates as a percentage of estimates from the FEH model for a duration of 6 hours and a return period of 1,000 years

A total of 71 sites were selected for model testing. These sites were selected primarily on the basis of raingauge record length and/or proximity to large reservoirs, and also to give good coverage of the UK. Rainfall frequency estimates were derived for the full range of durations from 1 to 192 hours (i.e. 8 days) and for return periods from 100 to 10,000 years. To illustrate the results, Figure 3 shows a map comparing estimates from the revised model with the FEH model for a 6-hour duration and a return period of 1,000 years. It can be seen that the estimates from the new model are generally lower than those from the FEH for most of England, Wales and Northern Ireland. The results in Scotland are more variable, with estimates in southern and north-west Scotland tending to reduce, while many of the estimates in the eastern part of the country are closer to or greater than those from the FEH. The location with the greatest positive departure from the FEH is a gauge in the Honister Pass at an altitude of 358m. At this location, the available data, especially hourly data, has increased considerably since the FEH analysis was undertaken, allowing much improved modelling of observed rainfall.

From the comparisons for all durations and return periods studied, two notable features emerge. Firstly, the estimates from the new model are higher over most of Scotland at the shortest durations, which is mainly due to the improvements to the hourly dataset. Secondly, the estimates from the new model tend to be lower than the FEH at high return periods, which is due mainly to the improved model of spatial dependence. At extremely high return periods, estimated rainfalls from the new DDF model are lower than the FEH model because the former uses an approximate straight line extrapolation on the Gumbel scale, while the latter has an exponential extrapolation.

Whilst FEH 10,000-year rainfall estimates commonly exceeded FSR PMP, this is rarely the case with estimates from the new model. According to the new model, the return period at which rainfall estimates equal FSR PMP increases with duration and is typically in the region of 100,000 years at about the 12-hour duration.

Table 1 summarises the results of comparisons between the new model, the FEH and FSR models and FSR PMP estimates for the 6-hour duration at six reservoir sites in the UK. It can be seen that most of the estimates from the new model are smaller than those from the FEH except for the lower return periods at the two reservoirs in Scotland. The results for the new model tend to be slightly higher than those from the FSR for return periods of 1,000 years and above, apart from the estimates for Clywedog. The new 10,000-year estimates are generally lower than those from the FSR model. Comparisons with estimates of 6-hour PMP derived from the FSR show that none is exceeded by the new 10,000-year frequency estimates, which is in line with the results for all durations.

Table 1. Rainfall frequency estimates for a duration of 6 hours at or near six UK reservoir sites (see location map above)

Reservoir (Gauge name)	Return period (years)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	6-h rainfall as % of FSR PMP		
					FSR (%)	FEH (%)	New (%)
Loch Ussie (Dingwall)	150	49	59	64	30	36	39
	200	52	64	66	31	39	40
	1,000	73	93	81	44	57	49
	10,000	117	162	99	71	98	60
Thorters (Nunraw Abbey)	150	65	69	75	37	39	42
	200	69	73	79	39	41	44
	1,000	95	103	101	53	58	57
	10,000	148	167	131	83	94	74
Ogston (Ogston Res.)	150	69	77	68	32	36	32
	200	73	83	73	34	39	34
	1,000	103	125	109	48	59	51
	10,000	170	228	156	80	107	73
Clywedog (Dolydd)	150	96	114	92	44	52	42
	200	101	123	97	46	56	44
	1,000	138	182	126	63	83	57
	10,000	215	318	169	98	145	77
Pen Ponds (Kew)	150	64	80	72	30	38	34
	200	69	86	76	32	40	36
	1,000	98	131	106	46	62	50
	10,000	162	239	163	76	113	77
Porth (St Mawgan)	150	68	78	77	34	40	39
	200	72	84	81	36	42	41
	1,000	102	124	103	52	62	52
	10,000	168	215	135	85	108	68

CONCLUSIONS

A project to revise some of the key elements of the FEH model of rainfall depth-duration-frequency has been described. Full details are available in the project report (Stewart *et al.*, 2009). Results from the new DDF model have been compared with the models published in the FEH and the FSR for a number of sites in the UK where sufficiently long raingauge records exist for a range of durations. The comparisons demonstrate that the new formulation of the model, which has been designed to apply to return periods from 2 to over 10,000 years, overcomes the shortcomings of the FEH model.

At the moment the new DDF model can only be fitted on an individual site basis and it requires relatively long raingauge records to be available to allow the estimation of the index variable, RMED. Further research is planned to generalise the results across the UK and to develop a software package to replace that currently available on the FEH CD-ROM 3 (CEH, 2009).

In recent years, a new approach to reservoir safety management has been developed using quantitative risk assessment (QRA) as an alternative to the current standards-based system (Brown *et al.*, 2008). The QRA approach is based on risk analysis and requires the assignment of probabilities to individual hazards such as overtopping. If future guidance to panel engineers is to be based on QRA, the concepts of PMF and the 10,000-year flood will be replaced by the need to quantify the probabilities of very extreme floods and the associated uncertainties. The new DDF model has been designed to provide estimates of the probability of such rare events where sufficient data exist.

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