defra
Department for Environment Food and Rural Affairs

Environment Agency

delivering benefits through evidence

Reservoir Safety – Long Return Period Rainfall

Volume 1 Technical Report (Part 2)

Project: FD2613 WS 194/2/39

Flood and Coastal Erosion Risk Management Research and Development Programme

Statement of use
This document provides details of the analysis undertaken during project WS 194/2/39 entitled *Reservoir safety: long return period rainfall* funded by Defra. The report describes a new model of rainfall depth-duration-frequency applicable to the UK, which is proposed as a replacement to that published in the Flood Estimation Handbook (IH, 1999). The report is intended to inform Defra and Environment Agency staff, reservoir panel engineers, consultants, contractors and other agencies and organisations involved in hydrological frequency estimation about the new model. Further work to develop a software implementation of the new model is ongoing.

Dissemination status: Publicly available

Keywords: Reservoir safety, extreme rainfall, Flood Estimation Handbook, rainfall frequency estimation, depth-duration-frequency model, spatial dependence, standardisation, annual maxima, FORGEX, PMP

Research contractor:
Ms Lisa Stewart, Centre for Ecology & Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxon. OX10 8BB (ejs@ceh.ac.uk)

Peter Dempsey, Met Office, FitzRoy Road, Exeter, Devon EX1 3PB (peter.dempsey@metoffice.gov.uk)

Professor Christopher Collier, National Centre for Atmospheric Science, School of Earth & Environment, University of Leeds, LS2 9JT (c.g.collier@leeds.ac.uk)

Professor Clive Anderson, Dept of Probability & Statistics, University of Sheffield, Sheffield S3 7RH (c.w.anderson@shef.ac.uk)

Defra project officer: John Goudie, Flood Management Division, Ergon House, Horseferry Road, London SW1P 2AL (john.goudie@defra.dsi.gov.uk)

Publishing organisation
Department for Environment, Food and Rural Affairs
Flood Management Division,
Ergon House,
Horseferry Road
London SW1P 2AL

Tel: 020 7238 3000 Fax: 020 7238 6187

www.defra.gov.uk/environ/fcd
© Crown copyright (Defra); 2013

Copyright in the typographical arrangement and design rests with the Crown. This publication (excluding the logo) may be reproduced free of charge in any format or medium provided that it is reproduced accurately and not used in a misleading context. The material must be acknowledged as Crown copyright with the title and source of the publication specified. The views expressed in this document are not necessarily those of Defra or the Environment Agency. Its officers, servants or agents accept no liability whatsoever for any loss or damage arising from the interpretation or use of the information, or reliance on views contained herein.

Published by the Department for Environment, Food and Rural Affairs (2013).

Joint Defra/Environment Agency Flood and Coastal Erosion Risk Management Research & Development Programme

Reservoir Safety – Long Return Period Rainfall

R&D Technical Report WS 194/2/39/TR
Volume 1 (Part 2)

Submitted: March 2010

Authors:

E. J. Stewart[1], D. A. Jones[1], C. Svensson[1], D. G. Morris[1], P. Dempsey[2], J. E. Dent[2], C. G. Collier[3] & C. W. Anderson[4]

[1] Centre for Ecology & Hydrology, Wallingford
[2] Met Office, Exeter
[3] National Centre for Atmospheric Science, School of Earth & Environment, University of Leeds
[4] Department of Probability & Statistics, University of Sheffield

Foreword

This report presents the results of a major project to develop a new statistical model of point rainfall depth-duration-frequency (DDF) for the UK. This is intended to replace both the Flood Estimation Handbook (FEH) model (Faulkner, 1999) and the present guidance given to Defra panel engineers (Defra, 2004) that the FEH rainfall estimates should not entirely replace the old Flood Studies Report (FSR) estimates of 1975.

Acknowledgements

Rainfall data have been supplied by the Environment Agency for England and Wales, by the Scottish Environment Protection Agency for Scotland, by the Met Office for locations throughout the United Kingdom, and by Met Éireann for locations in the Republic of Ireland near the border with Northern Ireland. The use of all these data is gratefully acknowledged.

The members of the Project Steering Group are thanked for their helpful comments on all aspects of the work involved in the project:

John Gosden, Jacobs (Chairman)
Dr Geoff Baxter, Environment Agency
Sir David Cox, University of Oxford
Paul Ditchfield, Defra
Marcus Francis, Jacobs
Fiona Geddes, Environment Agency
Dr Peter Mason, MWH Global
Professor Paul Samuels, HR Wallingford
Peter Spencer, Environment Agency
Professor Howard Wheater, Imperial College

Besides those listed as authors, CEH staff who made substantial contributions to the project included Fai Fung and Sonja Folwell.

Executive Summary

This report presents the results of a major project to develop 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 new model was constructed for estimating rainfall depths falling over durations ranging from 1 hour to 192 hours (8 days) for return periods ranging from 2 years to 10,000 years. However, in many locations it is capable of producing indicative estimates for higher return periods, up to 100,000 years.

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. In many locations, the FEH model was giving 10,000-year estimates considerably higher than the Flood Studies Report (FSR) probable maximum precipitation (PMP). This is used to calculate the probable maximum flood as a statutory part of the spillway design procedure for major reservoirs.

In this project, the framework of the FEH approach to rainfall modelling has been retained, but a number of key elements have been substantially revised. In particular, the Focused Rainfall Growth Curve Extension (FORGEX) methodology has been reformulated, and the dataset of annual maximum rainfalls, to which the final model is fitted, has been updated. The main improvements are:

- Data – the number of suitable hourly raingauges is more than double the total available to the FEH, giving much improved coverage in Scotland and south-west England. The data have been subjected to extensive quality control.

- Standardisation – by using SAAR and northing in addition to FEH's RMED, the new model removes more of the location-dependent variation in rainfall before combining maxima from networks of raingauges.

- Spatial dependence model – the new model allows for a reduction in spatial dependence (i.e. greater independence) between raingauges as return period increases.

- FORGEX – the FEH method of deriving rainfall growth curves has been improved to give a better fit to the network maxima and more gradual variation between locations.

- DDF model – 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 FEH, the new model does not increase exponentially if extrapolated beyond the range of return periods represented in the observed datasets.

The report presents comparisons of rainfall estimates from the new model with those from the FSR and the FEH models for 71 sites across the UK, 35 of which are close to impounding reservoirs. These show that, generally, estimates for the longer return periods are lower, especially in comparison with FEH. However, in Scotland estimates for the shortest durations have increased. These changes are due, respectively, to the improved spatial dependence model and improvements to the hourly rainfall dataset. In the majority of cases, the new 10,000-year estimates are lower than the FSR PMP.

Also presented in the report is a comparative assessment of the return periods of 26 major UK rainfall events from the period 1880 to 2006 derived from FSR, FEH and the new model. The estimated return periods from the new model are generally substantially higher than from the earlier models, but statistical arguments suggest that they are closer to what may be expected for the largest point-wise return period observed across a large number of years and a large number of raingauges.

Implementing the new model will be computationally intensive and will require new, detailed digital maps of median annual maximum rainfall (RMED) to be developed for durations ranging from 1 hour to 8 days.

The report sets out an implementation programme and makes wide-ranging suggestions for future research.

Contents Part 1

Glossary

Contents Part 2

Appendices: Volume 2

Glossary

AREA	Notional area covered by a network of gauges computed from average inter-gauge distance.
Areal reduction factor	A factor applied to a point rainfall for a given return period to give an areal average rainfall with the same return period (*note that several other definitions exist*).
D	Duration (length of the period over which rainfall is accumulated).
DDF	Depth-duration-frequency.
Discretisation conversion factor	A factor applied to annual maxima extracted from data at 1-hour or 1-day resolution to adjust them to correspond to ‘fully-sliding’ values.
F	Non-exceedance probability.
FEH	Flood Estimation Handbook (five volumes) (*Institute of Hydrology, 1999*).
Fixed duration maxima	Largest of all rainfall totals, where the duration considered coincides with the time resolution of the underlying data.
FORGEX	Focused Rainfall Growth Curve Extension methodology described in FEH Volume 2.
FSR	Flood Studies Report (five volumes) (*NERC, 1975*).
Fully-sliding maxima	The value of annual maximum that would be found by considering all possible time periods of the given duration, not limited by time resolution of data.
GEV	Generalised Extreme Value distribution.
ICE	Institution of Civil Engineers.
Index-flood method	A simple approach to standardisation, assuming that division of values by a site-specific value will explain all differences between distributions at different sites.
L-kurtosis	A measure of kurtosis (tendency to have long tails) of a distribution, based on L-moments.
L-moment ratios	Statistics such as L-skewness, constructed as the ratio of two L-moments.

L-moments	Summary statistics of a distribution, computed as linear combinations of the ranked observations.
L-scale	A measure of the spread of a distribution derived from L-moments.
L-skewness	A measure of skewness (lack of symmetry) of a distribution, based on L-moments.
lcmed	An L-moment based version of the coefficient of variation (L-scale/median).
M5	5-year return period rainfall (mm).
MCS	Mesoscale convective system, defined as a continuous cloud system of thunderstorms associated with a wide area of precipitation (*Houze, 1993*).
N	Actual number of gauges in a network.
N_e	Effective number of independent gauges in a network.
Netmax	Network maximum point (the highest annual maximum standardised rainfall within a network of raingauges).
ngy	The northing component of the National Grid Reference of a location, expressed in 1000 km units.
Orography	For a given location, variations in altitude and slope in the near and distant neighbourhood of the location.
PMF	Probable maximum flood.
PMP	Probable maximum precipitation.
Raingauge network	Any collection of raingauges from the available set of gauges, not restricted to any one original measuring authority, usually within a specified distance of a particular location.
ReFH	Revitalised Flood Hydrograph model (*Kjeldsen, 2007*).
RMED, *RMED*	Median of annual maximum rainfalls at a given site, different values for different durations.
rsaar1	A constructed variable based on SAAR.
SAAR, *SAAR*	Standard average annual rainfall (1961-1990) (mm).

Semi-sliding maxima	Contrasts with ‘fully-sliding maxima’, used to recognise that, in practice, rainfall data are not available for an arbitrarily fine resolution.
Sliding duration maxima	The FEH term for fully-sliding maxima. The maximum is taken across all totals of the given duration.
Spatial dependence	A general statistical quality corresponding to the tendency for high or low values to occur simultaneously at a collection of sites.
Spatial dependence model	In this project, a model where the effect of spatial dependence on the distribution of the maximum value across a collection of sites is represented.
Standardisation	Methods for creating a processed set of values in which the effects of explainable differences between sites have been eliminated.
Standardised rainfall	In this project, standardised rainfalls are created by adjusting to have a common median and to reduce differences in spread based on values of SAAR.
T	Return period (years).
x	Standardised rainfall.
y	Gumbel reduced variate.

Entries in italics are symbols used in equations

8. A new model of rainfall depth-duration-frequency

8.1 Introduction

The revised FORGEX methodology developed within the current project was described in detail in Section 7, with examples of both rainfall growth curves (standardised) and rainfall frequency curves (in mm) presented. This section discusses the development of a rainfall depth-duration-frequency (DDF) model which supersedes that presented in the FEH and is designed to provide estimates of rainfall frequency for a range of durations at any location in the UK. The DDF modelling step is carried out to ensure consistency between the frequency estimates for different durations, because, until this point, each duration has been treated separately. The model also allows extrapolation and has been specifically developed to provide rainfall estimates at the very high return periods relevant to reservoir flood risk analysis.

The new model was developed and assessed on the basis of the outputs of the revised FORGEX analysis for 71 test sites, described in Appendix G. These are the locations of raingauges with long daily and hourly records. Currently, model parameters can only realistically be estimated for any raingauge site where sufficiently long annual maximum series exist. This is because of the need to have good estimates of the median rainfall in order to convert the FORGEX results from standardised rainfall to actual rainfall. It is envisaged that a future research project will review the adequacy of the available digital maps of the variable RMED (the median annual maximum rainfall of the relevant duration). It will then be possible to provide gridded DDF model parameter estimates to allow rainfall frequency to be reliably estimated at any site of interest.

8.2 Information transferred from FORGEX

Since the current project has adopted an approach to the development of the DDF model similar to that taken by the FEH team, it is helpful to outline the main steps in the FEH procedure, which were as follows:

- FORGEX growth curves were derived for a number of sites for a number of key durations.
- Frequency curves (in mm) were derived from the growth curves by rescaling by the at-site RMED of the relevant duration.
- Discretisation conversion factors were applied to convert ‘fixed’ and ‘semi-sliding’ to ‘fully-sliding’ durations (in the terminology used in this report).
- The 6-parameter model was fitted to the estimated rainfalls at each site jointly for all durations and return periods.

The revised FORGEX program, which is described in Section 7, generates some empirical information about DDF (depth-duration-frequency) curves. For a given location, it generates estimates for rainfall frequency curves for rainfall maximum totals defined for a number of durations. In particular, it estimates rainfalls for fixed clock-hour 1-hour and 1-day maximum rainfall totals and for semi-sliding versions of maximum total rainfall for the other durations, where these are based on data held at either a 1-hour or 1-day resolution. The initial step in the analysis to derive DDF curves is to apply scaling factors to the FORGEX results to convert the rainfall amounts to a fully-sliding-interval basis: see Appendix J. The discretisation conversion factors used are set out in Table 8.1. It is envisaged that most applications of extreme rainfall estimation would require annual maxima for rainfall totals of a given duration interpreted in the fully-sliding sense.

Table 8.1 Factors for converting rainfall maxima from fixed- and semi-sliding durations to the fully-sliding duration basis

Hourly durations based on 1-hour resolution		Daily durations based on 1-day resolution	
Duration	**Multiply FORGEX by**	**Duration**	**Multiply FORGEX by**
1 hour	1.160	1 day	1.146
2 hours	1.080	2 days	1.072
4 hours	1.030	4 days	1.043
6 hours	1.019	8 days	1.025
12 hours	1.000		
18 hours	1.000		
24 hours	1.000		

The values in Table 8.1 for durations based on the 1-day resolution dataset have been revised from the values used in the DDF analysis implemented in the FEH. This follows an analysis carried out during this project in which the rainfall information available at the relatively fine resolution of 1 hour has been used to examine the relative behaviour of annual maxima, defined on both fixed- and sliding-window bases, for durations of 1 day and higher: see Appendix J. Adjustment factors like these are based on empirical analyses of data, such as described in Appendix J, as there is no known theory directly related to this question.

The present study has considered two types of output from the FORGEX procedure, on which the DDF model might be based. Fitting of the DDF model in the FEH procedure was undertaken based on extracting values of rainfall for selected return periods from the segmented lines that were the result of the FORGEX step. The first type of output considered in this project parallels this, except for the following points.

- A denser and wider set of return periods is used in the present project. The more extensive dataset available for this project allows rainfall for higher return periods to be estimated, and there has also been some effect from the revised spatial dependence model which also has the effect of allowing higher return periods to be estimated because the fitted model implies ’more independence’ at high return periods than the FEH model. In addition, the rule used in the FEH procedure for how large a return period can be estimated has been relaxed slightly in order to reflect the present project’s target of providing estimates of rainfalls with as high a return period as possible.

- Rainfall values for all 11 durations listed in Table 8.1 are considered, whereas for the FEH fewer durations were used in the final parts of the analysis.

Table 8.2 lists the sets of return periods extracted for the first type of output from FORGEX. These represent the return periods for which rainfall values are potentially extracted. For durations based on hourly data, the available data means that the highest return period actually available may be as high as 5,000 years in some locations with large number of gauges in the vicinity, but can be as low as 100 years. Similarly, the return periods available for durations based on the daily raingauge data may in some instances be as large as 50,000 years but may be as low as 1,000 years.

Table 8.2 Return periods at which FORGEX results are potentially extracted

Return period (years)					
2	5	10	20	50	100
200	500	700	1,000	1,500	2,500
3,500	5,000	7,000	10,000	15,000	25,000
35,000	50,000	70,000	100,000		

The second type of information output from the FORGEX procedure is the set of data points that FORGEX uses to fit the segmented lines that have been presented in Section 7. This is known as the ‘points’ dataset. Specifically, these consist of the network maximum rainfalls with associated plotting positions, together with the weights described in Section 7. These weights were specifically developed during the design of the revised FORGEX procedure to ensure that the lines fitted show reasonable behaviour both across durations for a single location, and in comparisons of the sets of lines as the target location is moved slightly. Note that the points dataset consists of *all* the points for large return periods used in the FORGEX procedure described earlier. The intention to use network maxima values from the largest radii only as a guide to the location of the lines is now accommodated by assigning lower weights to these points. However, points corresponding to return periods of lower than 2 years have been dropped from the DDF-fitting procedure to prevent these points, which would otherwise be given a relatively high weight, from having a bad effect on the fit at high return periods. The points dataset was considered as a potential replacement for the first type of output (or ‘lines’ dataset) within the procedure for fitting the DDF model because it seems best not to introduce the intermediate line-fitting step if it is not necessary. Fitting the new DDF model

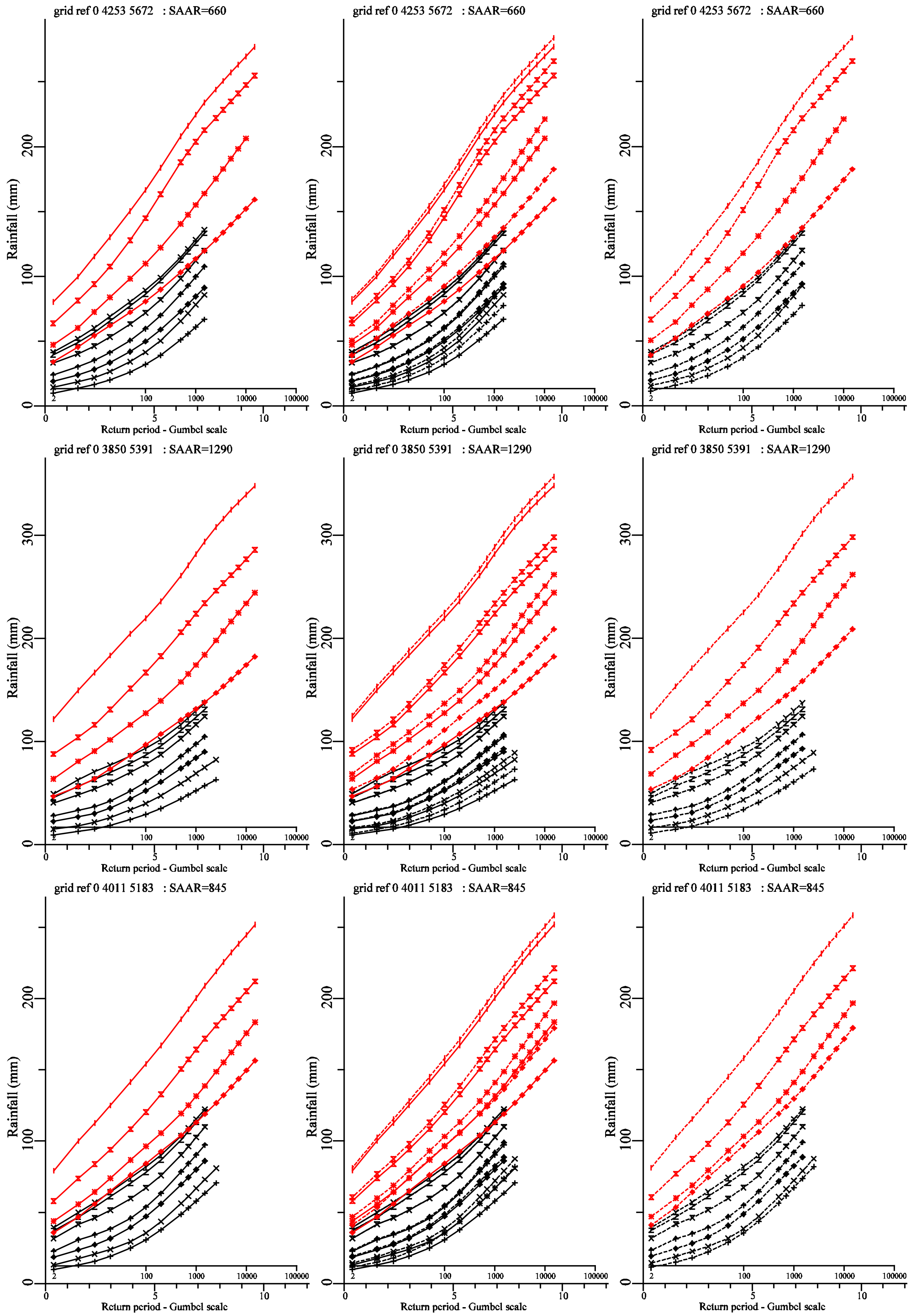

Figure 8.1a DDF curves plotted against return period on a Gumbel scale, showing the raw FORGEX results (full line) and the discretisation-adjusted values (dashed line). Red lines are for daily durations and black lines are for hourly-based durations.

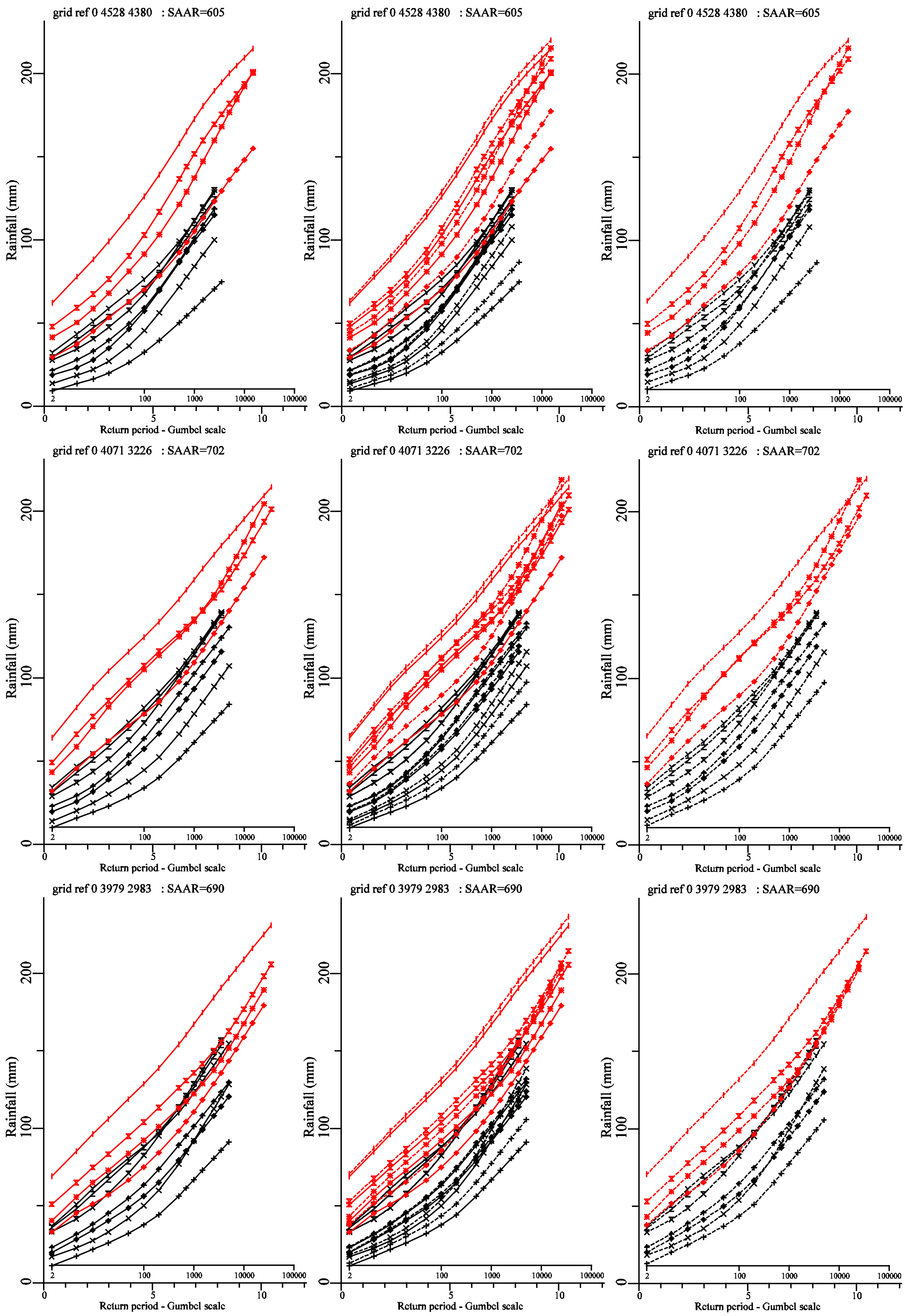

Figure 8.1b DDF curves plotted against return period on a Gumbel scale, showing the raw FORGEX results (full line) and the discretisation-adjusted values (dashed line). Red lines are for daily durations and black lines are for hourly-based durations.

to the points dataset is the procedure recommended for implementation. The lines dataset is retained for expository purposes as the behaviour of the results of FORGEX is seen more clearly in plots based on these data.

Figure 8.1 shows some examples of the results from the FORGEX procedure and of the results of applying the discretisation conversion factors to create adjusted values. For six different target locations, Figures 8.1(a) and (b) show, in each row and as separate plots, the lines dataset output from FORGEX results in unadjusted form, a comparison of the unadjusted and adjusted results and the adjusted results alone. The separate curves in these plots relate to the different durations listed in Table 8.1, with the hourly durations appearing in black, with the 1-hour duration lowest, and with the daily durations in red, with 1-day lowest. Lines for the same duration are marked by the same symbol.

The example results in Figure 8.1 show that, while application of the discretisation conversion factor does serve to improve the ordering of the curves when moving from the hourly-based durations into the daily-based durations, it is not completely successful. In some cases, the DDF values for the sliding 24-hour duration lie above those for the sliding 1-day duration (that is, adjusted from the fixed 1-day duration), whereas these should notionally be identical. In addition, the expected ordering is sometimes contradicted among the adjusted DDF values within the hourly durations and within the daily durations.

8.3 DDFs using Extreme Value Theory

When ‘Extreme Value Theory’ is applied in the context of DDF curves, its role is often limited to defining how the rainfall amounts should vary with return period, and not how they should vary with duration. A recent example of this occurs in a paper by Muller *et al.* (2008), where reliance is placed on a previously established functional form for the relation with duration. Almost inevitably, the relationship to return period is suggested to be in the form of a Generalised Extreme Value (GEV) distribution where, although the shape parameter of the GEV may be allowed to vary with duration, some constraints are required so that the rainfall-frequency curves for different durations do not cross.

There are some results in extreme value theory which can provide some initial guidance about potentially appropriate forms of DDF curves. The following is based on results given by Leadbetter *et al.* (1983, p217). The results given are for maxima of a standardised Gaussian process. To remove the effect of this standardisation, the following assumptions are made. Let $X_D(t)$ be the duration-*D* total ending at time point *t.* Note in particular that this is not the annual maximum but rather a continuous-time version of ’typical’ duration-*D* totals . It is assumed that

$$E(X_D(t)) = aD \quad (8.1a)$$

and

$$\mathrm{var}(X_D(t)) = bD\,. \quad (8.1b)$$

The second assumption might be modified slightly if a more detailed model for serial dependence were used, but it should be a reasonable approximation for large durations if there is no long-range dependence. For the quantity a in the first equation,

$$a = \frac{SAAR}{K}, \tag{8.2}$$

where, if the duration *D* is measured in units of hours, *K* is the number of hours in a year ($K = 365.25 \times 24 = 8766$). Therefore, for the purposes here, *a* could be assumed to be known. The parameter b would need to be determined empirically.

To match constants here to the theory in Leadbetter *et al.* (1983, p217), set

$$c = (2\log T)^{\frac{1}{2}} \tag{8.3}$$

where (only here to match the notation of Leadbetter) T is the length of a year in hours (so notionally it is the same as K, however it is a feature of the theory associated with the use of a Gaussian assumption and so it may be best kept separate).

With some simple assumptions, the theory says that the asymptotic distribution of the maxima of the standardised totals is Gumbel with location parameter

$$u = c + c^{-1}(A - \log D), \tag{8.4}$$

and scale parameter $\alpha = c^{-1}$. Here A is a constant related to the dependence in the underlying rainfall (in the continuous-time rainfall intensity time-series). It is known (for example, Daniels, 1982) that both the distribution form and the shift and scale constants derived from asymptotic theory for extreme values from a Gaussian process are very poor representations of the true distribution of the maximum of a moderate number of samples.

The quantiles of the maxima of standardised rainfalls (mean zero, unit variance) would be given by

$$\begin{aligned} r(T,D) &= c + c^{-1}(A - \log D) + c^{-1}y \\ &= c + c^{-1}(A - \log D) + c^{-1}\{-\log(-\log(1 - T^{-1}))\} \end{aligned} \tag{8.5}$$

where T is the return period in years and y is the Gumbel reduced variate.

Finally the quantiles of maxima of rainfall would be given by

$$\begin{aligned} R(T,D) &= aD + (bD)^{\frac{1}{2}} r(T,D) \\ &= aD + (bD)^{\frac{1}{2}}\{c + c^{-1}(A - \log D) + c^{-1}y\} \end{aligned} \tag{8.6}$$

Given that both *b* and *c* (and *A*) are 'unknown', this could be revised to

$$R(T,D) = aD + (D)^{\frac{1}{2}}\{d + e(y - \log D)\} \quad (8.7)$$

where d and e are to be estimated and a is known. However, using the same coefficient for y and for $\log D$ is somewhat open to question.

The above theory is not directly useful in this project because using a Gumbel distribution for any particular distribution is counter-indicated by direct data analyses. However, it would be reasonable to propose replacing the Gumbel distribution in these formulae by a Generalised Extreme Value distribution. This would result in a proposal for how the location and scale parameters of such a distribution might vary with duration.

Some fairly drastic assumptions are made in deriving the above formulae, and it would be necessary to check how well any given functional form accords with data-derived results. Because of the difficulties of dealing with constraints on the variation of the shape parameter of the GEV distribution, it is not proposed to use the above approach here. However, it is of some interest to assess the usefulness of the conclusions that use might be made of the known value of SAAR, and that the spread of the distribution of annual maxima might vary proportionally to the square root of the duration. This is done in Figure 8.2, where the results shown in Figure 8.1 are recast so as to plot the rainfall amounts against the square root of the duration. The lines represent different return periods as detailed in Table 8.2, with the lowest line being for a return period of 2 years. The line styles and colours are as before, except that these plots include an additional green full line which represents the mean value of the 'typical' rainfall total for the given duration.

The plots in Figure 8.2 provide another opportunity to examine the effectiveness of the sliding-scale adjustment.

Using the square root of the duration in plotting Figure 8.2 is reasonably successful. Not only does it provide a scale on which the different durations are more easily distinguished than if the results were plotted against the untransformed duration, but there does seem to be some merit in the transformation in that it produces a relationship which is approximately linear for large durations. Note that the suggestion of the square root transformation derives from the semi-explicit treatment of the rainfall quantities as deriving from the total over a given duration. It is derived as the standard deviation of a total: a linear relation would hold exactly given that the underlying quantities are uncorrelated, but a linear relation for large durations should hold given that statistical dependencies have a short-range in time. The success of the square-root transformation suggests that there should be some benefit in attempting to derive a model in which use is made of the fact that the underlying rainfall quantities of different durations, from which maxima are extracted, are actually totals.

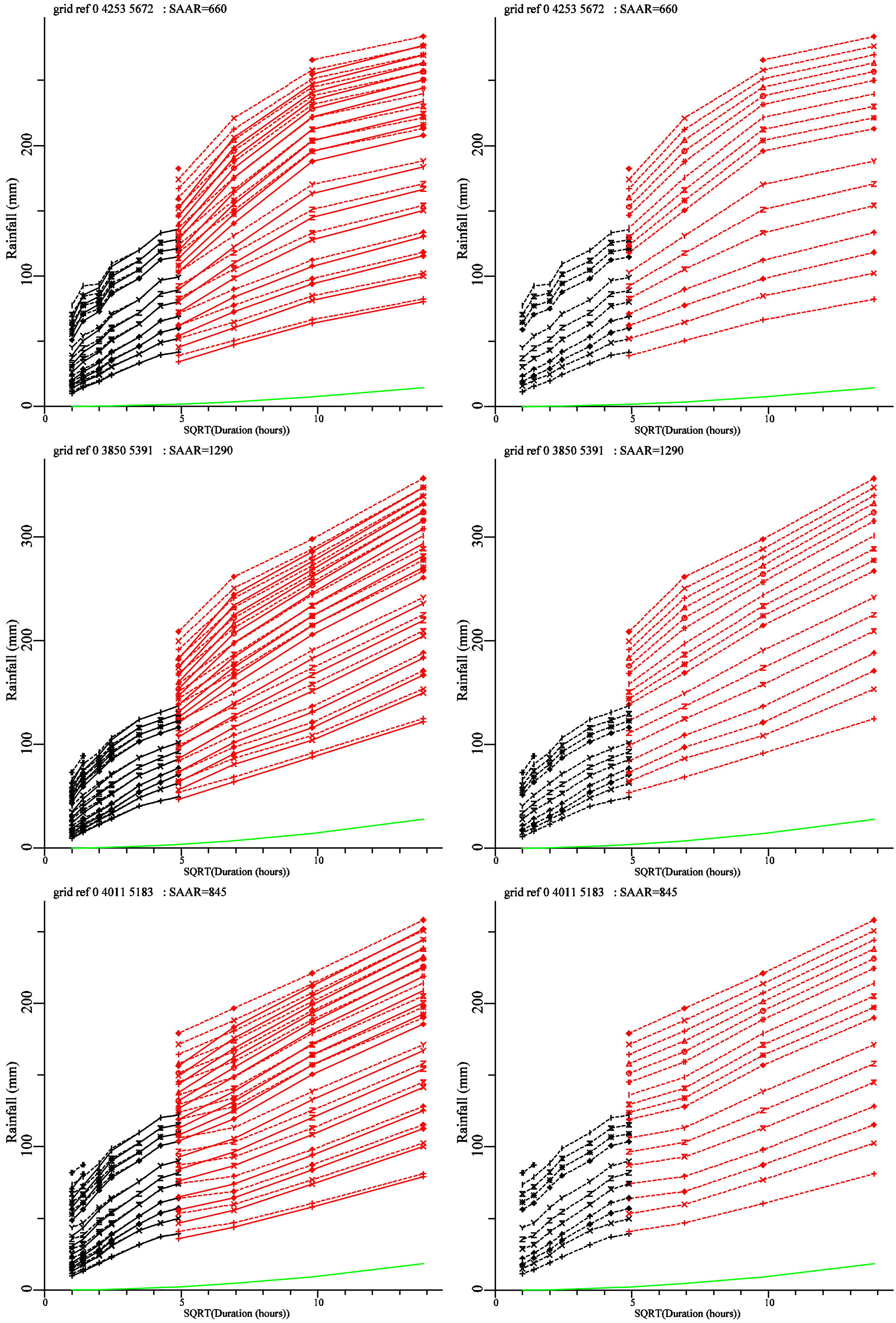

Figure 8.2a DDF curves for return periods 2 to 10^5 years, plotted against the square root of duration, showing the raw FORGEX results (full line) and the discretisation-adjusted values (dashed line). Red lines and black lines are for daily and hourly durations respectively. The mean rainfall for the duration is the green line.

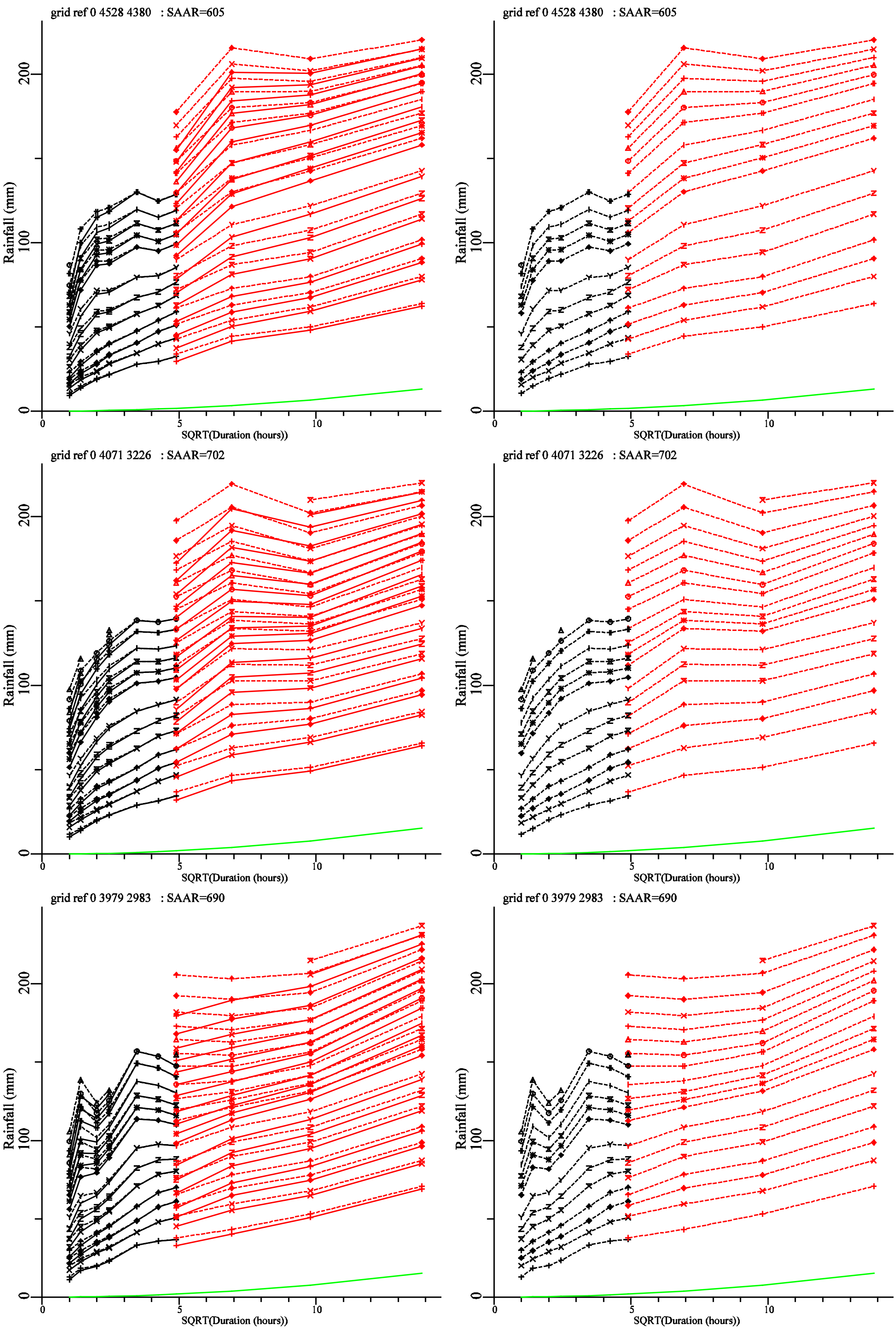

Figure 8.2b DDF curves for return periods 2 to 10^5 years, plotted against the square root of duration, showing the raw FORGEX results (full line) and the discretisation-adjusted values (dashed line). Red lines and black lines are for daily and hourly durations respectively. The mean rainfall for the duration is the green line.

8.4 The model for depth-duration-frequency curves

The main reason for not using the GEV distribution as the basis of a DDF model is that the GEV family of distributions is not flexible enough to reproduce the type of re-curving behaviour seen in Figure 8.1 even for a single duration. It would also be unable to match the inter-relationships between the curves for different durations that are apparent in the empirical data. The approach taken here is that the DDF curves produced should follow the behaviour of the adjusted FORGEX results as closely as possible, but without allowing the frequency curves for different durations to contradict each other.

The discussion in Section 8.3 prompts the idea that a DDF model can be based on treating the quantities involved in a way that makes use of the fact the rainfall values concerned are totals across different durations. One family of distributions for which explicit results are available for totals of underlying quantities is the family of Gamma distributions. Specifically, if the underlying quantities being totalled each are independent realisations from a Gamma distribution with the same scale parameter and possibly different shape parameters, then the total has a Gamma distribution for which the scale parameter is unchanged and the shape parameter is the sum of the individual shape parameters. This leads to a first version of a basic model for distributions varying with duration (which will later be interpreted as a distribution of annual maxima of different durations): the distribution function, $F(x;D)$, for rainfalls of duration D would be

$$F(x;D) = G(x;\alpha,\beta(D)), \qquad (8.8)$$

where G is the distribution function of a Gamma distribution with scale parameter α and shape parameter β. Here the shape parameter would be specified as a function of the duration D. Using a function more general than just having β proportional to D can be interpreted as making an allowance for serial dependence in the continuous-time rainfalls. No explicit model for such a dependence is set down and a derivation of the Gamma distribution for totals of serially dependent values is not relied on here. Any justification will be purely empirical. The assumption of a Gamma distribution in the basic functional form above allows the definition of a family of frequency curves which will not cross as the duration varies, provided that $\beta(D)$ is an increasing function of D.

The above idea starts from a basis where individual components of a duration-total are independent, or only modestly dependent. Here the 'individual components' are the shorter-duration rainfalls which are summed to form the longer-duration total. A second idea starts from a basis of high dependence in which individual components within a duration-total would be essentially constant within an event (but differ between events). In this case, an appropriate model would have distribution functions for different durations in which the scale parameter would be proportional to duration. Based on this idea, it seems reasonable to extend the above model in a first basic form by saying that the distribution function would be of the form

$$F(x;D) = G(x;\alpha(D),\beta(D)) \,. \qquad (8.9)$$

Again, provided that $\alpha(D)$ is an increasing function of D, the distribution functions do not cross.

The basic family of distributions outlined above is not general enough to provide the re-curving behaviour seen in Figure 8.1. A first extension of the model is to use a mixed distribution of the form

$$F(x;D) = p_1 G(x;\alpha_1(D),\beta_1(D)) + (1-p_1)G(x;\alpha_2(D),\beta_2(D)) \,. \qquad (8.10)$$

Here $\alpha_1(D)$ and $\alpha_2(D)$ are two increasing functions of D for the scale parameters and, as before, $\beta_1(D)$ and $\beta_2(D)$ are also two increasing functions of D. Again, the simple mixture model means that frequency curves corresponding to this first extension will not cross as the duration varies.

Given the supposed usefulness of extreme value theory, it seems relevant to make a further extension of the family of distributions so that it has the potential to include distributions similar in shape to the Generalised Extreme Value distribution. This is done by defining the family of distribution functions to be of the form:

$$F(x;D) = \left\{p_1 G(x;\alpha_1(D),\beta_1(D)) + (1-p_1)G(x;\alpha_2(D),\beta_2(D))\right\}^{\nu} \,. \qquad (8.11)$$

Here the value ν is allowed to vary as one of the parameters of the family of distributions. Again, this formulation guarantees that the frequency curves corresponding to this final version will not cross as the duration varies.

It is possible to use extreme value theory to show that, if the frequency curves of distributions in the above family are plotted against a Gumbel reduced variate then, for large enough return periods, the curves will approach straight lines. Therefore, the family selected will mean that the problem of extrapolating to extremely high return periods that was experienced with the FEH procedure (that the rainfalls had an exponential relationship to the reduced variate) will not arise here.

After some experimentation using datasets outlined in Section 8.1, the functions defining the scale and shape parameters have been defined to be of the following two forms:

$$\alpha(D) = \upsilon_0 + \upsilon_1 D \qquad (8.12a)$$
$$\beta(D) = \gamma_0 + \gamma_1 D + \gamma_2\left\{1-\exp(-\gamma_3 D)\right\} \,. \qquad (8.12b)$$

The experimentation did not suggest the need for the scale parameter β to increase more strongly as a function of D as would be the case if there were long-range dependence.

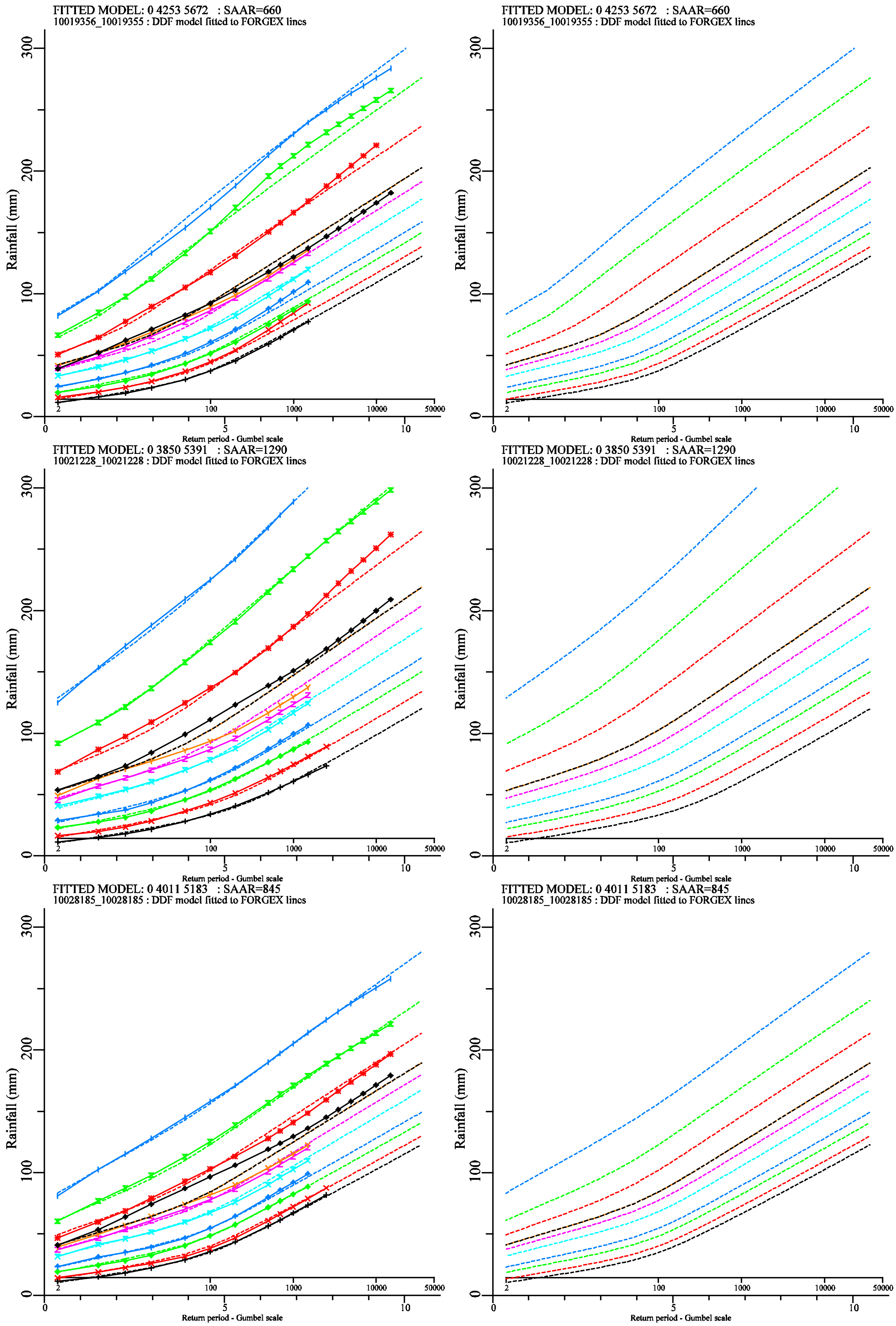

Figure 8.3a DDF curves plotted against return period on a Gumbel scale, showing the discretisation-adjusted FORGEX results (full line) and the modelled values (dashed line). This plot represents the FORGEX "lines" output and the DDF model fitted to these data.

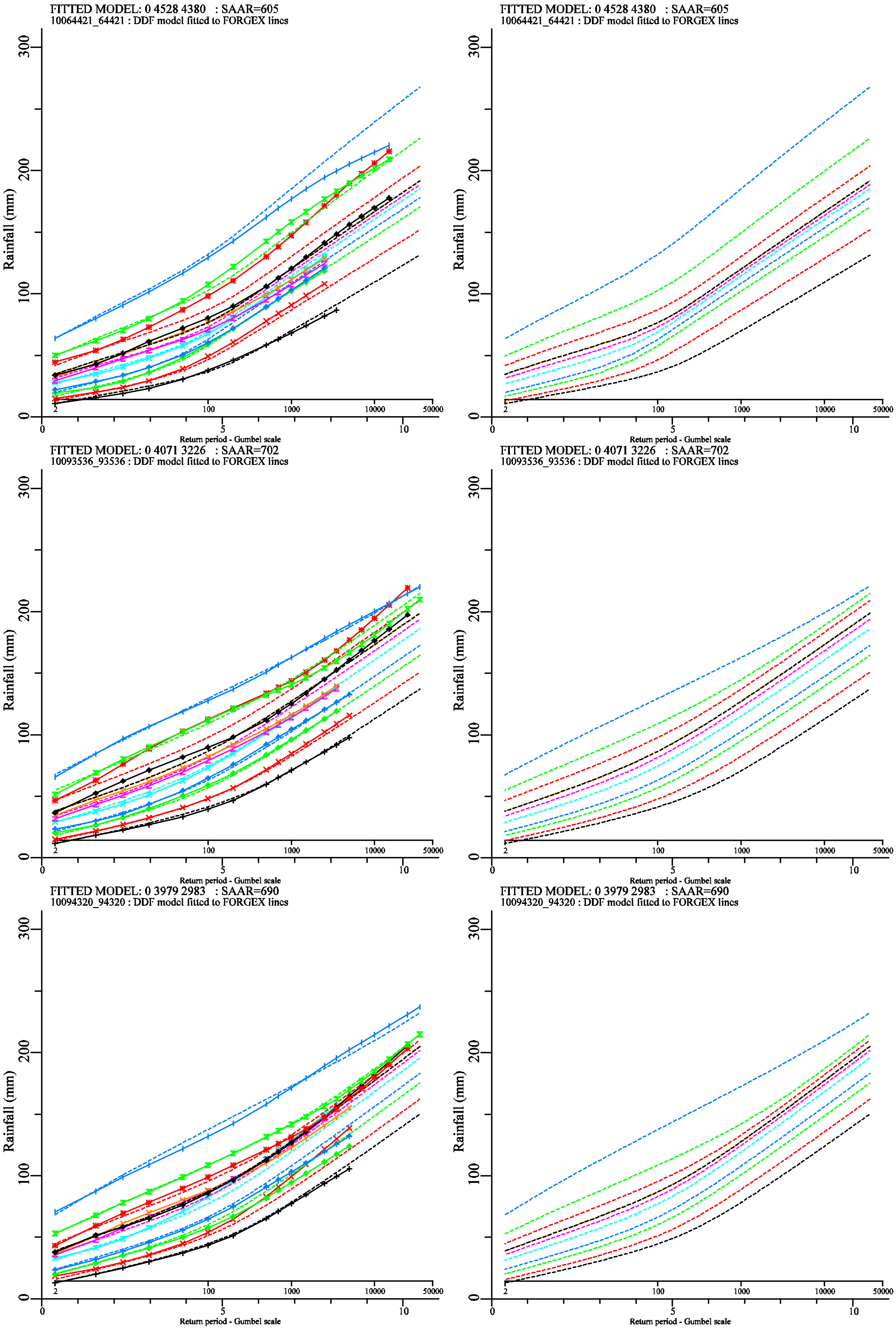

Figure 8.3b DDF curves plotted against return period on a Gumbel scale, showing the discretisation-adjusted FORGEX results (full line) and the modelled values (dashed line). This plot represents the FORGEX "lines" output and the DDF model fitted to these data.

Figure 8.3 shows the results of fitting this family of distributions, which has 14 parameters. Here the model is fitted to the ’lines’ output from FORGEX. Fitting was implemented by using a weighted least-squares objective function to match the quantiles of the modelled distribution to the empirical results from FORGEX. In the case of the lines dataset, the return periods used are the return periods provided by the FORGEX program, as outlined in Section 8.2. In the case of the points dataset, the objective function uses the same weights as those used in the FORGEX procedure for fitting the lines. Therefore essentially the same objective function is used for fitting as in the FORGEX procedure, except that here the weights which were used to control the smoothness of the line-segments do not occur.

Figure 8.3 shows, for the same locations as used in Figure 8.1, some examples of the results of fitting the DDF model above to the results from the FORGEX procedure after the discretisation conversion has been applied. For each location, two separate plots are included. The first shows a comparison of the adjusted FORGEX values with the modelled values, while the second shows the modelled values alone so that the behaviour of the DDF as the duration changes can be more easily seen. The separate curves in these plots relate to the 11 different durations listed in Table 8.1, with the 1-hour duration lowest, and the 8-day duration highest. Lines for the same duration are marked by the same colour. In the case of the DDF model, 10 curves are visible as the 24-hour and 1-day results are identical.

It can be seen that the suggested family of distributions has a reasonable degree of flexibility in that the overall behaviour of the FORGEX curves is reproduced to a good extent. The major differences between the two sets of curves arise where the FORGEX curves are not consistent across durations.

The behaviour of the fitted frequency curves for high return periods appears to be reasonable.

Figure 8.4 shows the modelled DDF curves plotted against the square root of the duration. These plots are similar in nature to those in Figure 8.2 and include the same target locations. The modelled results in Figure 8.4 are given for all combinations of return period and duration even if the FORGEX procedure concluded that it could not provide estimates. Note that the same applies to Figure 8.3, but the effect is more evident here.

Once again the main differences between the modelled frequency distributions and the FORGEX results occur where there are inconsistencies between the FORGEX results for different durations. In fact, this form of plot serves to highlight such occurrences. One commonly occurring case of this is where there are moderate differences between the 24-hour and 1-day results from the adjusted FORGEX procedure. The modelled curves for these two cases are always forced to be identical. However, the modelled curves do seem to be a reasonable compromise between the inconsistent values.

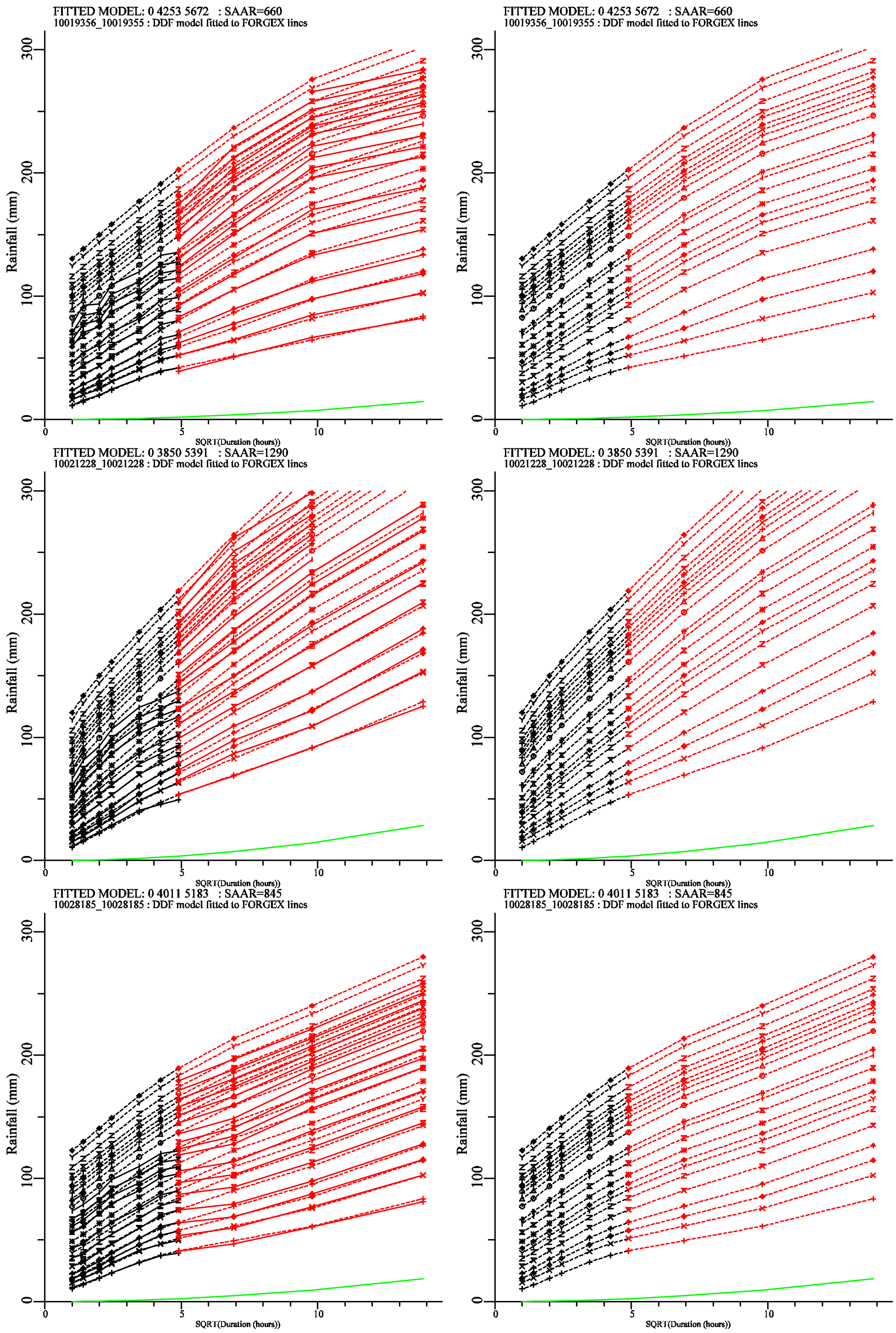

Figure 8.4a DDF curves for return periods 2 to 10^5 years, plotted against the square root of duration, showing the discretisation-adjusted FORGEX results (full line) and the modelled values (dashed line). Red and black lines are for daily and hourly durations respectively. The mean rainfall for the duration is the green line.

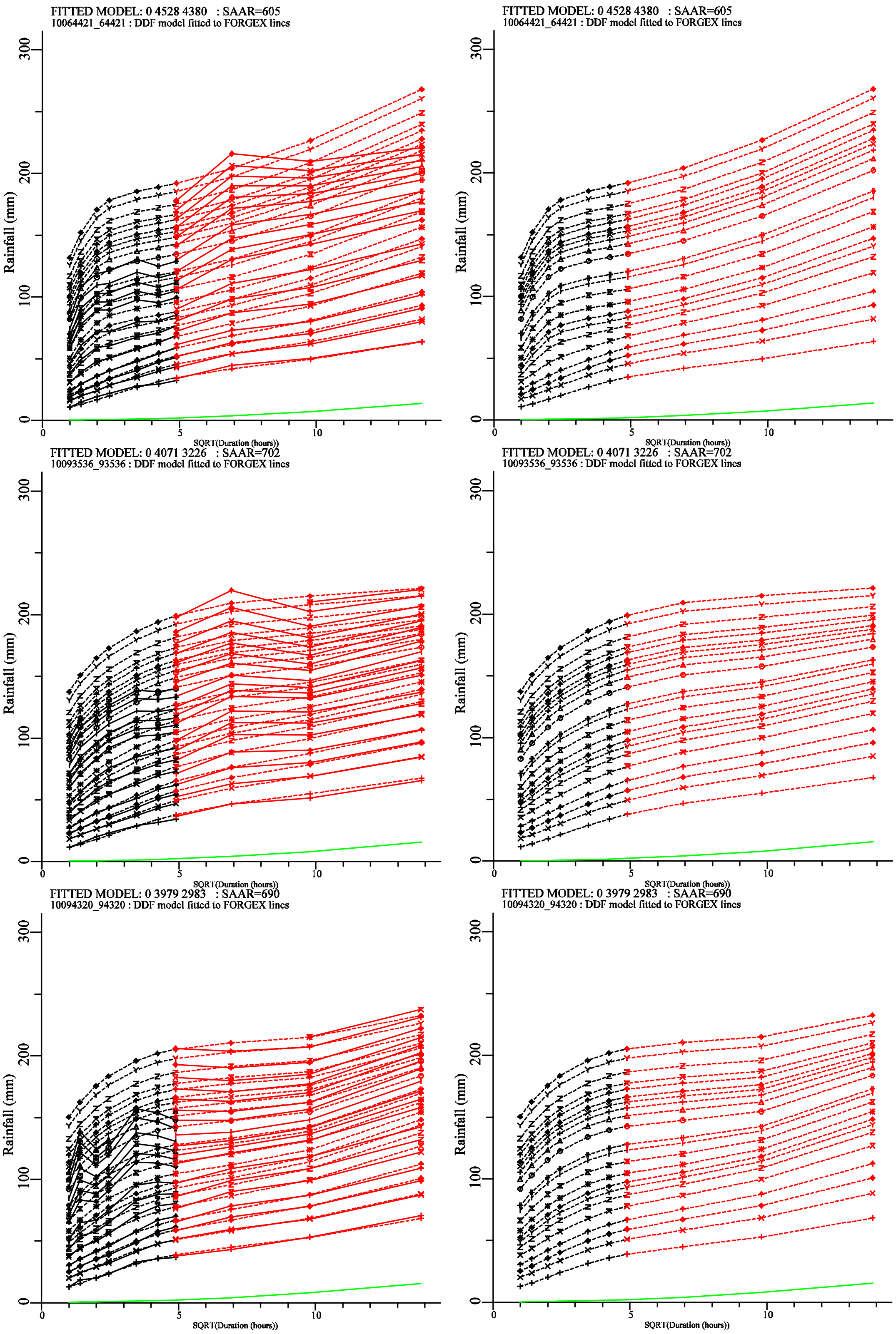

Figure 8.4b DDF curves for return periods 2 to 10^5 years, plotted against the square root of duration, showing the discretisation-adjusted FORGEX results (full line) and the modelled values (dashed line). Red and black lines are for daily and hourly durations respectively. The mean rainfall for the duration is the green line.

Figure 8.5 shows examples of fitting the DDF model to the ’points’ output from FORGEX. These examples represent the same locations as used in Figure 8.3, and they are shown on the same scales so that a comparison can be made. While there are differences in detail between the DDF models fitted to the ’lines’ and ‘points’ outputs, the ability of the DDF model to fit either dataset seems roughly the same.

Figure 8.6 shows, for the same six locations as in Figures 8.3 and 8.5, comparisons of the DDF models fitted to the ’lines’ and ‘points’ outputs. Here, the results are shown out to extreme return periods for two reasons. Firstly, the results illustrate the behaviour of the extrapolation to high return periods. The structure of the model selected is such that the extrapolation is a straight line when plotted on the Gumbel scale, in contrast to the exponential increase inherent in the DDF model used by the FEH. Secondly, they provide examples of results that may be of interest to those thinking of implementing cost-benefit analysis for reservoir design. Of course, the large range of return periods does give scope for the differences to be seen in the results of fitting the same model to two versions of the same data. On these plots, the upper end of the return-period scale is at 10^7 years, while the model results are plotted as lines ending at a return period of 10^8 years. The vertical blue dashed lines are intended to help to indicate the extent of extrapolation inherent in the model results. These two lines represent the upper limits assigned within the FORGEX procedure to the return periods for which estimated rainfalls can reasonably be deduced from the procedure. One line (always the lower value) indicates an upper limit for the 1-hour duration, while the second is the limit for rainfalls of 1-day duration. These limits vary from location to location depending on the numbers of gauges, and the lengths of their records, that are available within the 200 km radius of the FORGEX procedure. Therefore, values derived from the DDF model for return periods to the right of these limits would be putting considerable reliance on the extrapolation assumptions inherent in the DDF model.

Some alternative formulations for the DDF model presented above have been considered, and, in some cases, given initial tests. These include the following modifications:

- Replacement of the above function form in Equation (8.11), in which a single power is applied after forming the mixture, by one in which two different powers are applied before forming the mixture distribution. This would entail having a single extra parameter.
- Replacement of the Gamma distribution here, in its special role as a distribution where the behaviour of the shape of the distribution of totals is known, by a continuous version of the Binomial distribution. This would involve an extra two parameters. Using this distribution would mean that the fitted DDF curves would always correspond to bounded distributions. There would also be the possibility of using one Gamma and one Beta distribution.
- Replacement of the underlying mixture distribution in Equation (8.10) with a model representing the maximum of two random variables rather than the present probability-weighted selection of random variables. This would allow reduction in the number of parameters by one.

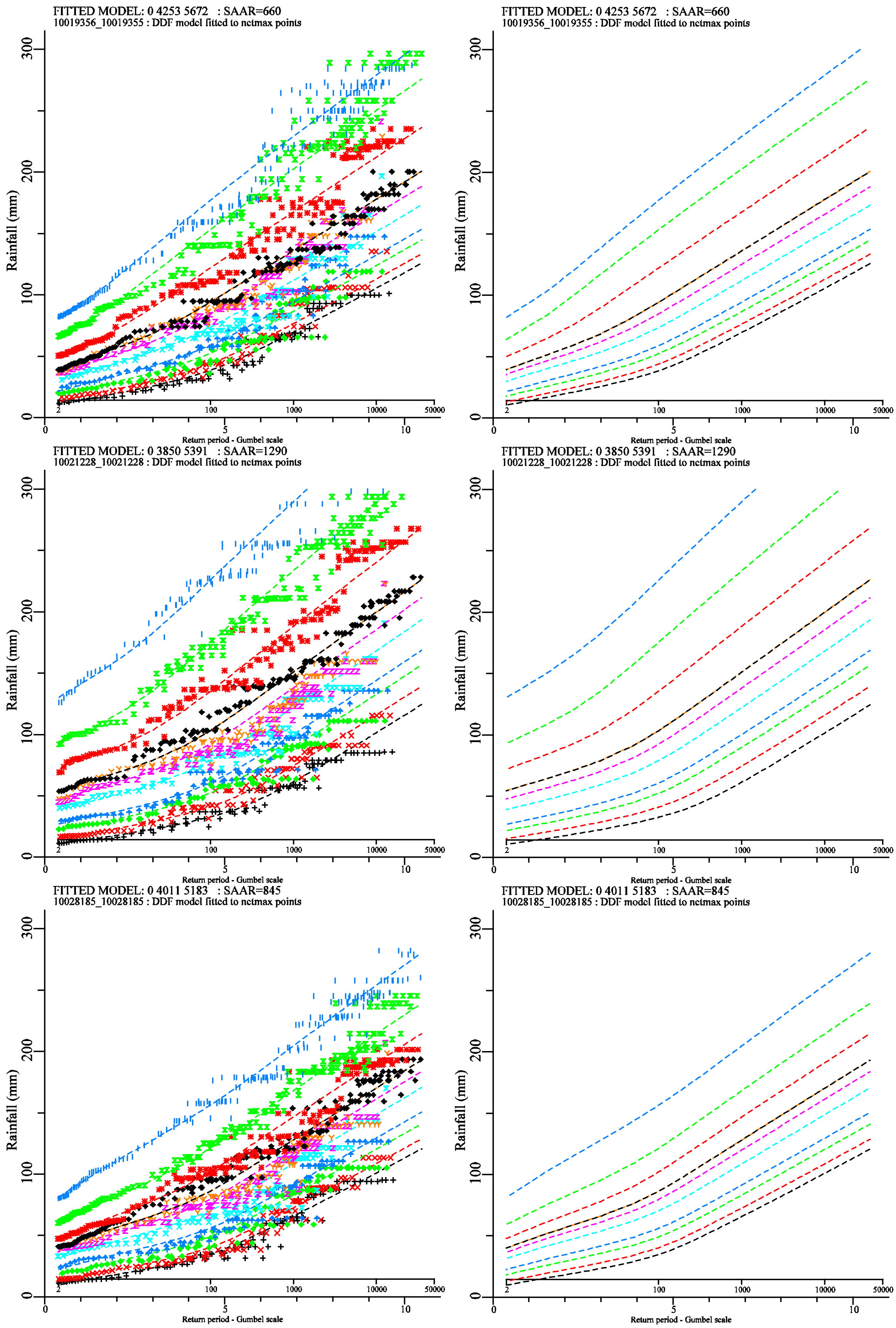

Figure 8.5a DDF curves plotted against return period on a Gumbel scale, showing the discretisation-adjusted FORGEX results (full line) and the modelled values (dashed line). This plot represents the FORGEX 'points' output and the DDF model fitted to these data.

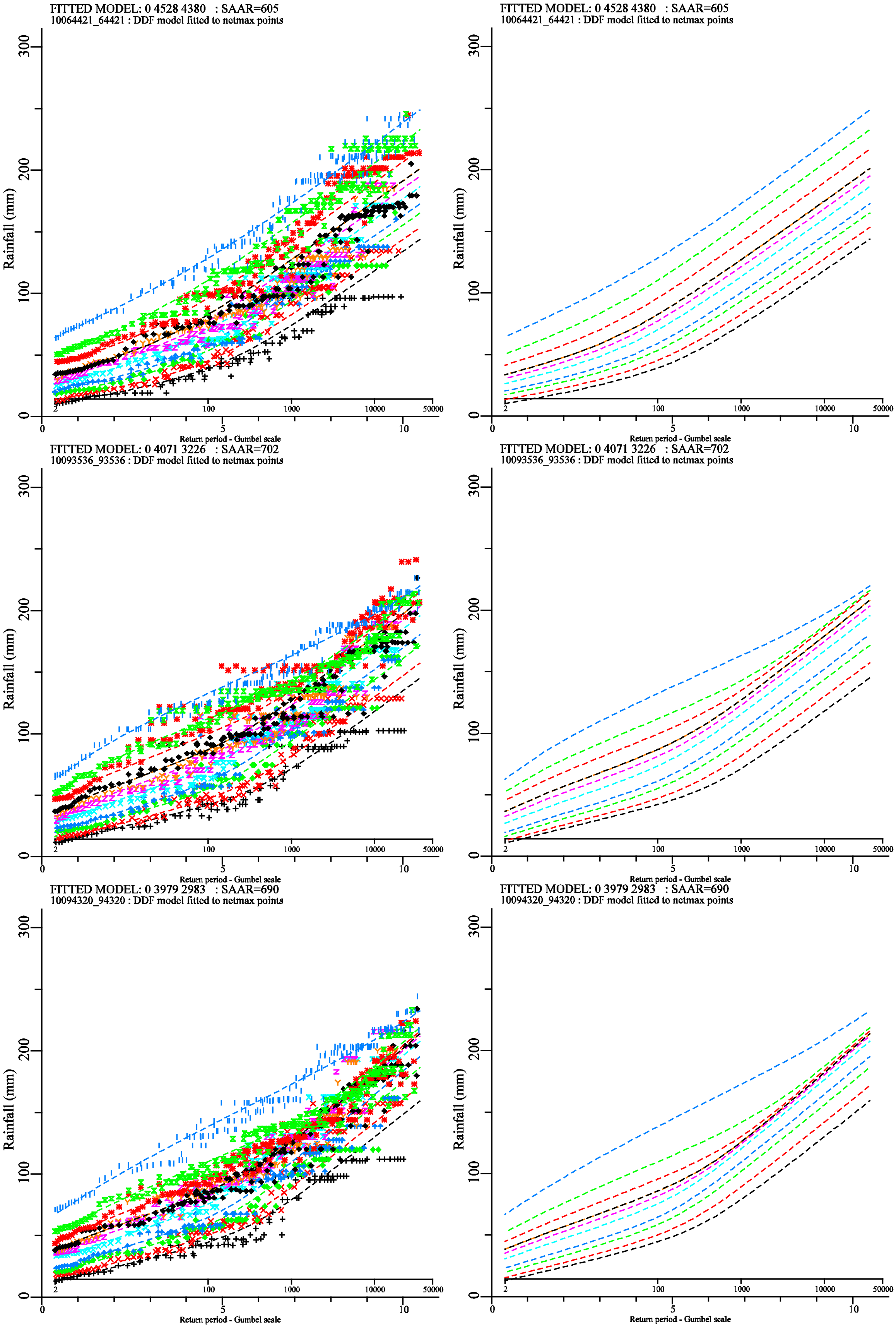

Figure 8.5b DDF curves plotted against return period on a Gumbel scale, showing the discretisation-adjusted FORGEX results (full line) and the modelled values (dashed line). This plot represents the FORGEX "points" output and the DDF model fitted to these data.

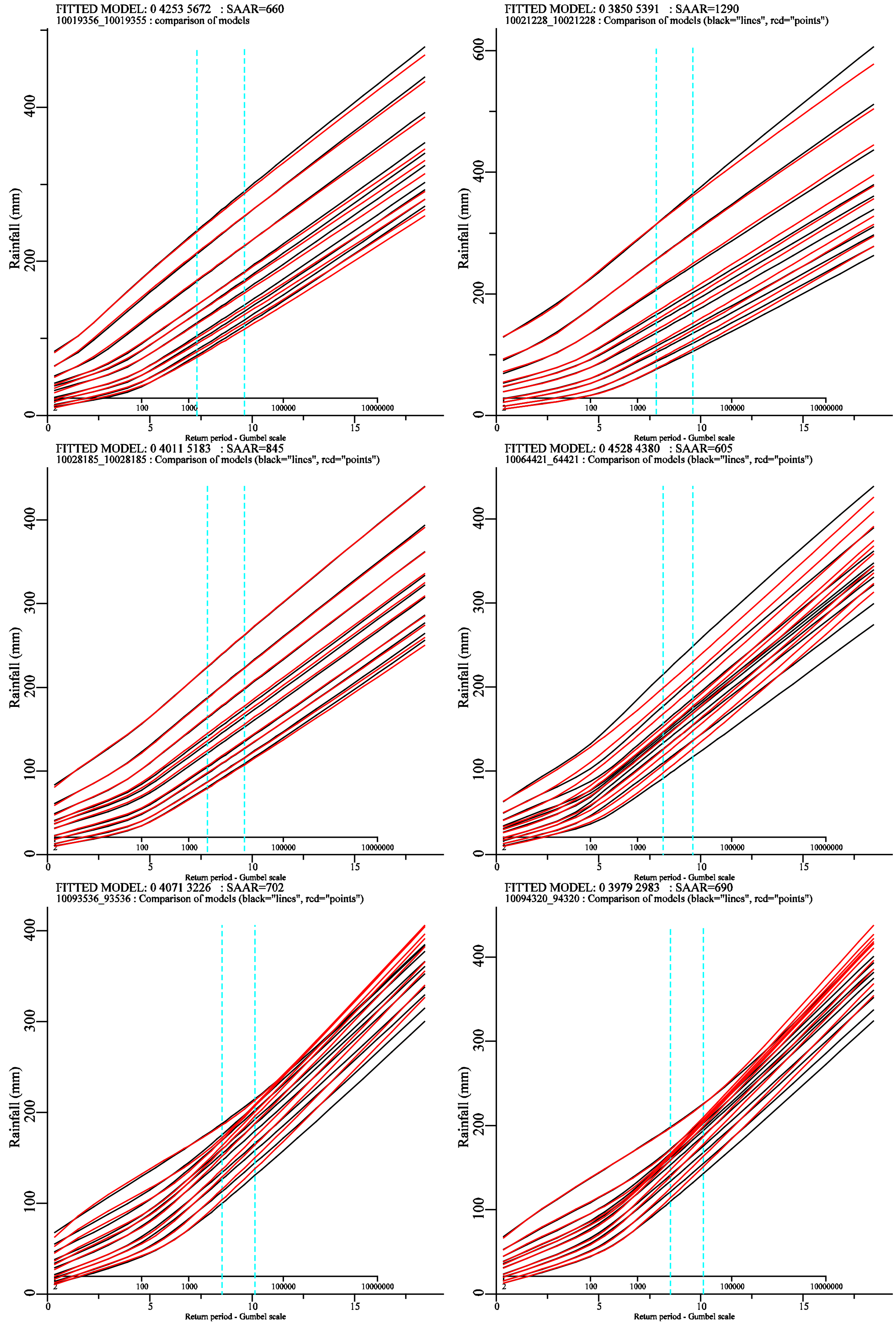

Figure 8.6 Comparison of DDF models fitted to the discretisation-adjusted FORGEX lines (black lines) and to the netmax points (red lines). The vertical blue-dashed lines show the extent of information from hourly (left line) and daily gauges (right line).

In addition, consideration has been given to other extensions of both the basic model implemented here, and of the above modifications. These include power-transformations on the reduced variate scale so as to provide increased flexibility in encompassing curvature in rainfall frequency curves at high return periods. There was not time to fully assess any of the above alternative formulations.

Trials of the basic form of model on the 71 long-record sites suggest that it should be adequate. The model has also been applied to a further selection of sites based on the extreme event database listed in Appendix B, and this revealed no further problems. A full discussion of both sets of results is given in Section 9. Logic suggests that preference is given to the DDF model fitted to the network maximum points used within FORGEX, rather than to that fitted to the segmented lines created as output by the FORGEX procedure. This will avoid the intermediate step of data summarisation which would otherwise be included if the FORGEX lines were used.

8.5 Summary

This section has outlined the development of a depth-duration-frequency model for rainfalls in the UK. It is based on an extended form of a mixture of Gamma distributions in which the parameters of the Gamma distribution components are allowed to vary with duration. This formulation takes advantage of some basic properties of the Gamma distribution, whereby the shapes of the distributions of totals over different durations can be dealt with in a single family of distributions.

The DDF model presented here seems broadly adequate in representing the observed data that are available. Two particular features of the model need some consideration, and these may lead to further developments of the model in future:

- The DDF model has 14 parameters, which may be thought too many on general grounds. Even with this number of parameters, there are some minor concerns over the model’s ability to represent some observed variations of growth curves with duration. However, the present approach to fitting these models requires long computation times, which argues against further complication.
- The structure of the DDF model leads to a particular behaviour in its extrapolation to large return periods which is inherent in its formulation. Specifically, this behaviour corresponds to the fitted lines from the model on plots such as Figures 8.3, 8.5 and 8.6 becoming straight lines at high return periods. This restriction on behaviour may be important if estimates of rainfall for extremely long return periods are required.

While these are valid concerns, the present practical need for generally available estimates of extreme rainfalls suggests that it would be most pragmatic to develop such estimates on the basis of the present model, subject to any procedural improvements related to computation speed that can reasonably be achieved.

9. Example results for selected locations

9.1 Introduction

In this section, the rainfall estimates obtained from the new DDF model are compared with those from the FEH and FSR models and with the FSR PMP. Here, the FEH and FSR estimates are derived from the published form of the relevant DDF model and therefore do not use the extended datasets that are now available. This section gives a comparison of the ‘new’ estimates produced by this project with two alternative sources of estimates currently used in the UK. It also provides a comparison of extremes actually observed at selected long-record locations with the predictions of the various models.

Two sets of locations are used for the comparisons. These are the full set of 71 test gauges, which were primarily selected on the basis of record length and/or proximity to reservoirs (see Appendix G for details), and the locations of the extreme rainfall events recorded between 1880 and 2006 that equal or exceed 70 per cent of FSR PMP (see Appendix B for details).

9.2 Comparisons at the locations of the 71 test gauges

9.2.1 Comparison with FSR and FEH rainfall frequency estimates

For durations of 1, 6, 24 and 192 hours, and return periods of 100, 150, 200, 1,000 and 10,000 years, maps have been produced to show the ratio of the new rainfall estimates to those from the FEH and FSR DDF models. Selected maps, for durations of 1, 6 and 24 hours and return periods of 150 and 10,000 years, form Figures 9.1 to 9.12. (The full set of maps, with the exception of the 150-year return period, forms Appendix K.) Note that no FSR values have been computed for Northern Ireland because the digital versions of the FSR maps only cover Great Britain.

The most notable features of the selected maps are:

- the 10,000-year estimates from the new model are considerably lower than those from the FEH, the reasons for which are discussed below;
- the new 150-year estimates for the 1-hour duration are considerably higher than both the FEH and the FSR estimates for most Scottish locations; this is consistent with the observation in Section 7.4 about the effects of the extension of the hourly dataset;
- there is a good consistency between the new estimates and those from the FSR over large parts of the country, including most of England and Wales, for the 150-year return period for the 6 and 24-hour durations, the reasons for which are discussed below; and
- the considerably higher estimates from the new model for Honister Pass in the Lake District, when compared with both FEH and FSR; this is not

consistent with the discussion in Section 7.5 (that the new standardisation method leads to a reduction at this location) and is probably due to the previous methods not adequately representing the spatial variability of the median rainfall in this mountainous area, and the fact that, as a consequence, they underestimate at this particular location.

The full set of maps in Appendix K highlights a further notable feature:

- the general agreement of all three methods at 192-hour (8-day) duration for the 100 and 200-year return periods.

Table 9.1 Details of featured locations (extract from Table G.1)

Near impounding reservoir (R)	Long record (L)	Very high SAAR location (V)	Name of daily gauge	Easting of daily gauge	Northing of daily gauge	Grid (0 GB, -1 NI)	Altitude of daily gauge	Number of 1-day annual maxima	SAAR at daily gauge	Number of 24-h annual maxima	Dam reference number	Dam name	Dam risk category
R			Dingwall	2538	8593	0	7	22	793	19	2714	Loch Ussie	B
R	L		Nunraw Abbey	3594	6700	0	197	33	824	23	471	Thorters	A
	L		Cornhow S Wks	3150	5222	0	98	30	1503	25			
		V	Honister Pass	3225	5135	0	358	20	3510	12			
R	L		Ogston Resr	4380	3598	0	102	39	791	40	367	Ogston	A
R	L		Dolydd	2874	2904	0	297	31	1876	25	117	Clywedog	A
R	L		Kew	5171	1757	0	5	110	591	95	2073	Pen Ponds Upper Lake, Richmond	A
R	L		St Mawgan	1872	641	0	103	40	1004	32	383	Porth	B
	L		Aldergrove	3147	3809	-1	63	34	867	57			

Nine locations have been selected as featured sites in order to illustrate in more detail the differences between the models. These locations are listed in north to south order in Table 9.1. This table is an extract from Table G.1, which shows the complete test set, and the first three columns show the criteria for inclusion of the gauges in this test set. The locations of these featured sites are circled on the maps in Figures 9.1 to 9.12. For each of these locations, the following outputs are presented as figures and tables:

- Plots, for durations of 1, 2, 6, 24 and 192 hours, showing rainfall frequency curves from the FSR, FEH and the new method, together with the FSR PMP values. Also featured on these plots are the observed annual maxima from hourly and daily gauges at the site, labelled 'H' and 'D' respectively, which allows a comparison with the results of a traditional single-site frequency analysis. The maxima have been plotted using plotting positions given by the Gringorten formula as described in Section 7.2. These plots are the even numbered figures from Figure 9.14 to Figure 9.30. Note that the FSR method has an upper limit of 10,000 years. Whilst this is also true of the FEH method (and it is recommended that it is applied with caution above 1000 years), its equations have here been applied up to 100,000 years for comparison with the new method. These plots relate to rainfall maxima for sliding durations. Separate sets of observations are marked for '24 hours' and for '1 day', each having been adjusted by the factors in Table 8.1 to make them equivalent. Different values are obtained from these two underlying sources of data, whereas the modelled values are the same for these cases.

- Facing each of these plots is a plot of the data that were used to construct the new DDF model, the output from the new FORGEX procedure. These are the odd numbered figures from Figure 9.13 to Figure 9.29. When comparing a pair of plots it should be noted that (a) the vertical axis scales usually differ, and (b) the FORGEX plots are for fixed durations, whilst the DDF plots are for sliding durations. The rainfall for many sliding durations will be higher than for the equivalent fixed duration, by the factors given in Table 8.1. Note that the thumbnail location map on the FORGEX plot does not show the secondary search radius; the map on the DDF plot fully represents the area from which raingauges have been used.

- Tabulations (Tables 9.2 to 9.10) covering all the durations and return periods (except 100 years), showing the rainfalls from the three methods (the new DDF model and the FEH and FSR DDF models), the FSR PMP, and the ratios of the three estimates to FSR PMP.

This additional material helps to explain the origins of the percentages which have been mapped in Figures 9.1 to 9.12. In particular, the following can be observed:

- The flatter nature of the new DDF curves at higher return periods in comparison with the FEH results explains the low ratios displayed in the maps showing the new estimates as a percentage of the FEH values for the return period of 10,000 years (Figures 9.3, 9.7 and 9.11).

- Figures 9.22 and 9.24 show a good agreement between the new and the FSR curves up to around the 500-year return period for 6 and 24-hour durations for the selected sites in central England and central Wales respectively. There is a strong contrast between these curves and the higher FEH lines. In these respects, these plots are typical of many of the sites in England and Wales.

- The degree to which the FEH and FSR methods have underestimated the rainfall at Honister Pass at the 24-hour and 192-hour durations is well illustrated by Figure 9.20, in which the values from the site gauges agree well with the new curves. For the shorter durations, there is less agreement with the new lines, though this could be due to the short record length of the hourly gauge.

9.2.2 Comparison with FSR PMP

One of the reasons for the commissioning of this project was the concern that the FEH 10,000 year rainfall often exceeded the FSR PMP. This is demonstrated in Tables 9.2 to 9.9, which show that for the eight featured GB sites over the four featured durations the FEH 10,000 year rainfall exceeds the FSR PMP for 22 out of the 32 estimates. For the new model, this has fallen to 5 out of 32, with four of these being accounted for by the Honister Pass site, at which PMP may have been underestimated by the FSR due to the nature of the topography and insufficient local data.

According to the new model, the return period of the FSR 24-hour PMP is greater than 100,000 years at seven of the eight featured GB sites. For the 2-hour duration, the corresponding figure is three out of eight. A summary of this comparison for all of the 66 test sites in Great Britain is given in Table 9.11: recall that digital estimates of FSR PMP were not available for Northern Ireland. In particular, Table 9.11 shows, for the five featured durations, the number of sites at which the new DDF model concludes that the value of PMP provided by FSR has a return period of over 100,000 years. One interpretation of these results is that, according to the new model, the return period of the FSR PMP increases with duration from 1 hour to 24 hours and then reduces slightly at 192 hours. Figure 9.24 typifies this relationship. Various explanations could be put forward for this, including errors in FSR PMP that vary with duration, systematic errors in the new model that vary with duration, and a real variation in the return period of PMP with duration, which might depend on the interpretation of the notion of ‘PMP’ used for the FSR study.

9.2.3 Comparison with site-based estimates

The agreement of the estimates from the new DDF model with the site-based estimates is substantially better than for the FEH and FSR estimates. However, this might be expected because the new estimates make full use of the more recent records at the site whereas the older estimates do not. Nevertheless, the comparison here provides a check that there is no disagreement between the locally observed records and the results from the new procedure which brings in information from a widespread region.

(This page is blank to align the following figures in pairs on opposite pages.)

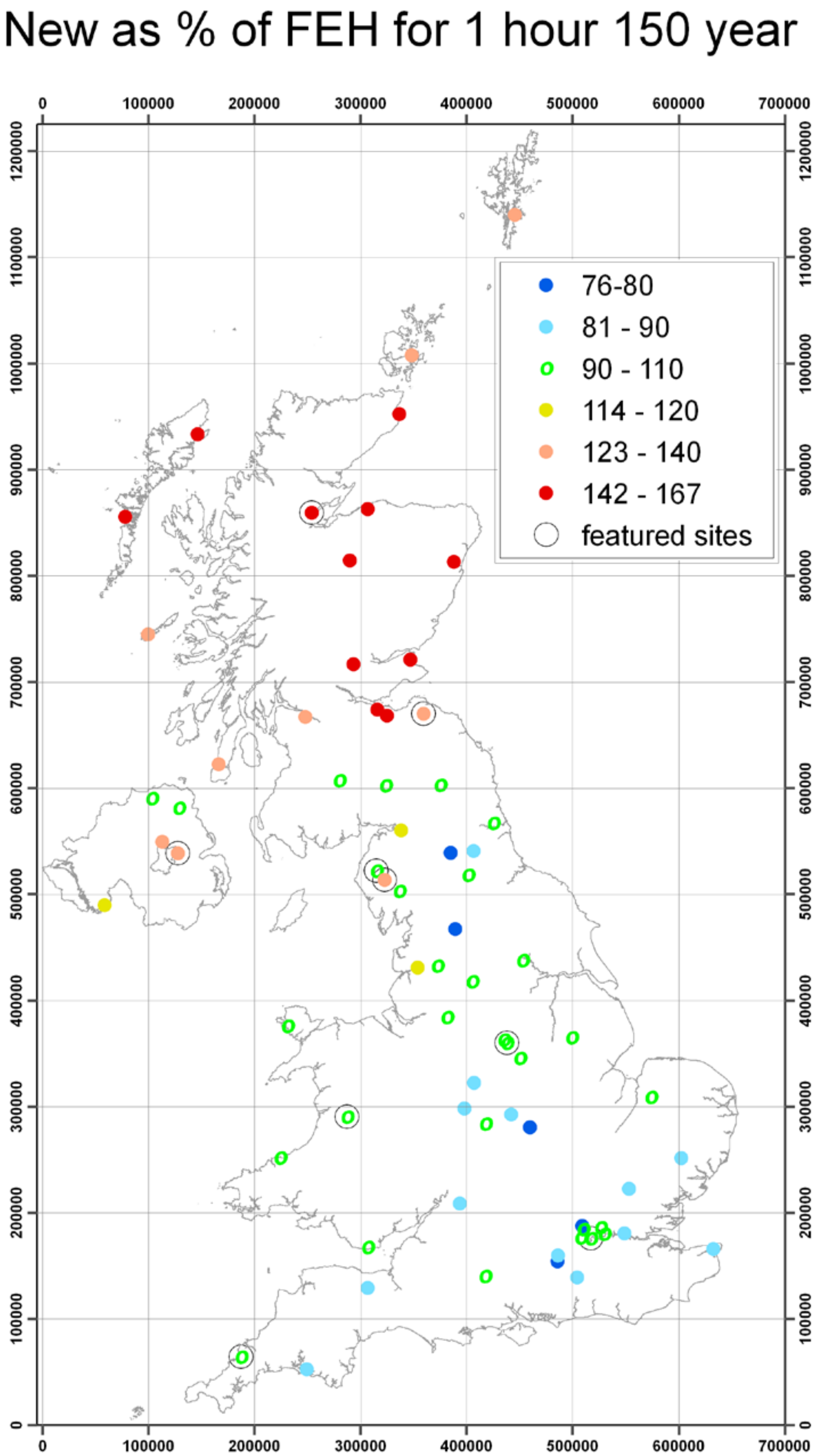

Figure 9.1 New rainfall estimates compared with FEH for 1-hour duration, 150-year return period

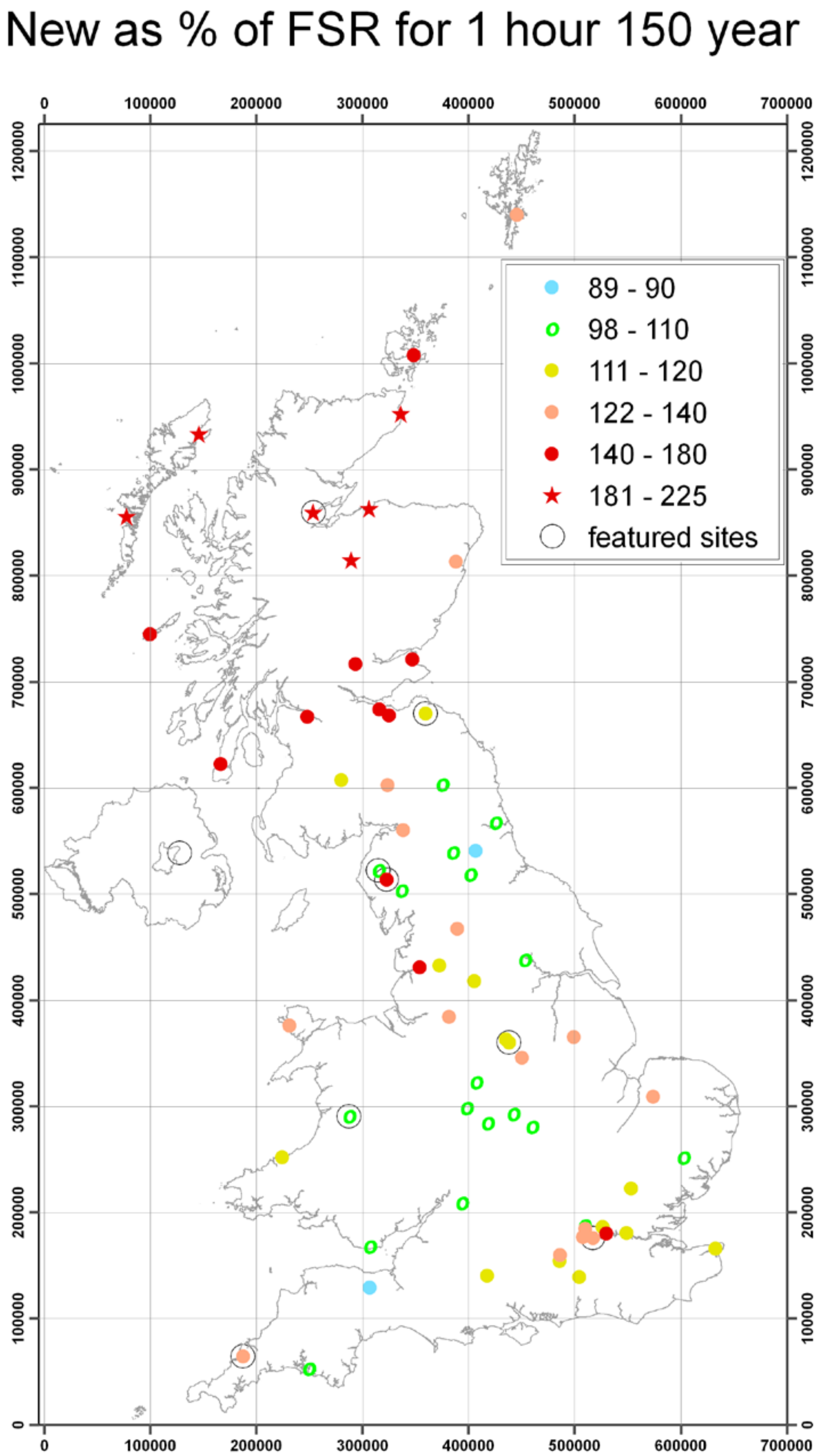

Figure 9.2 New rainfall estimates compared with FSR for 1-hour duration, 150-year return period

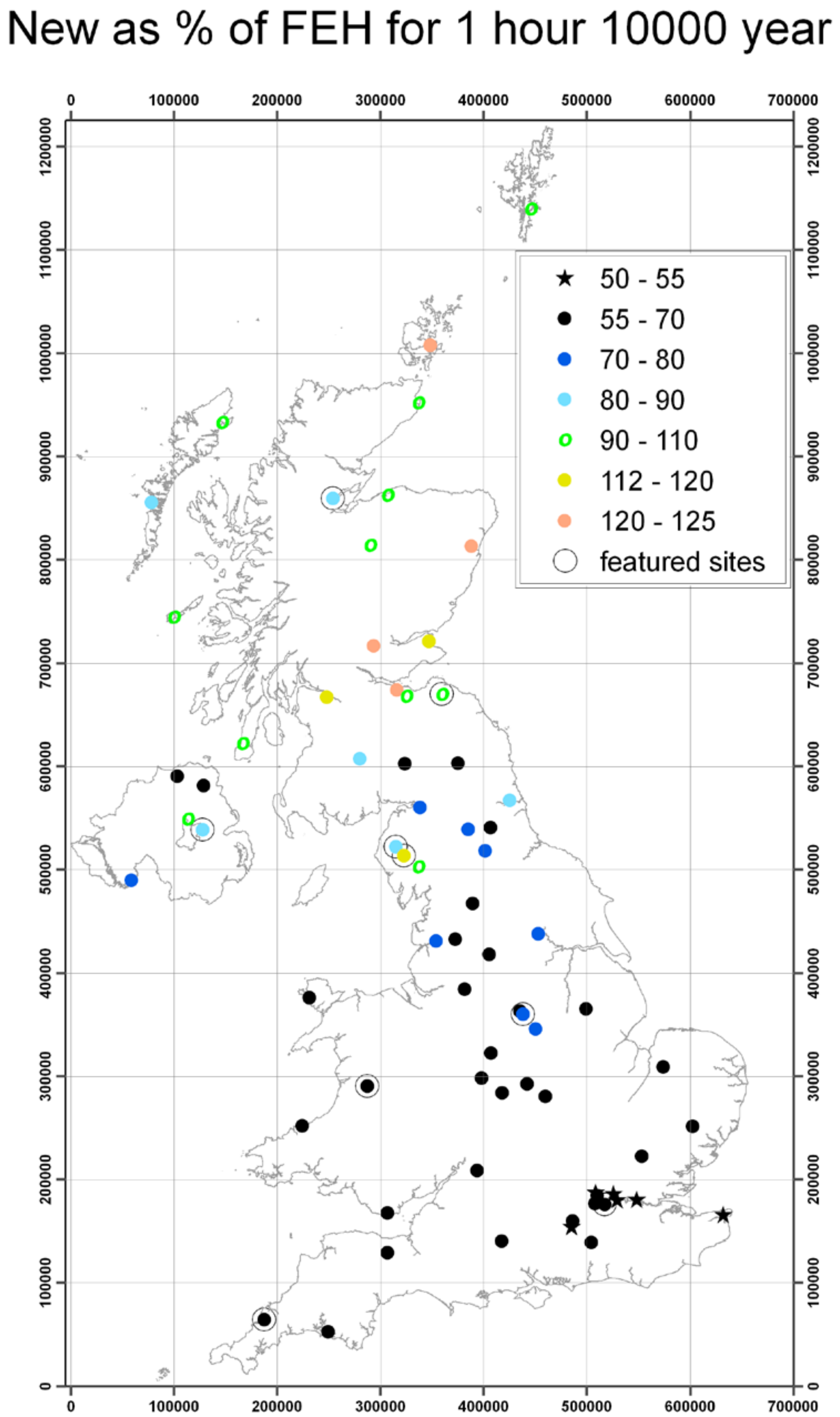

Figure 9.3 New rainfall estimates compared with FEH for 1-hour duration, 10,000-year return period

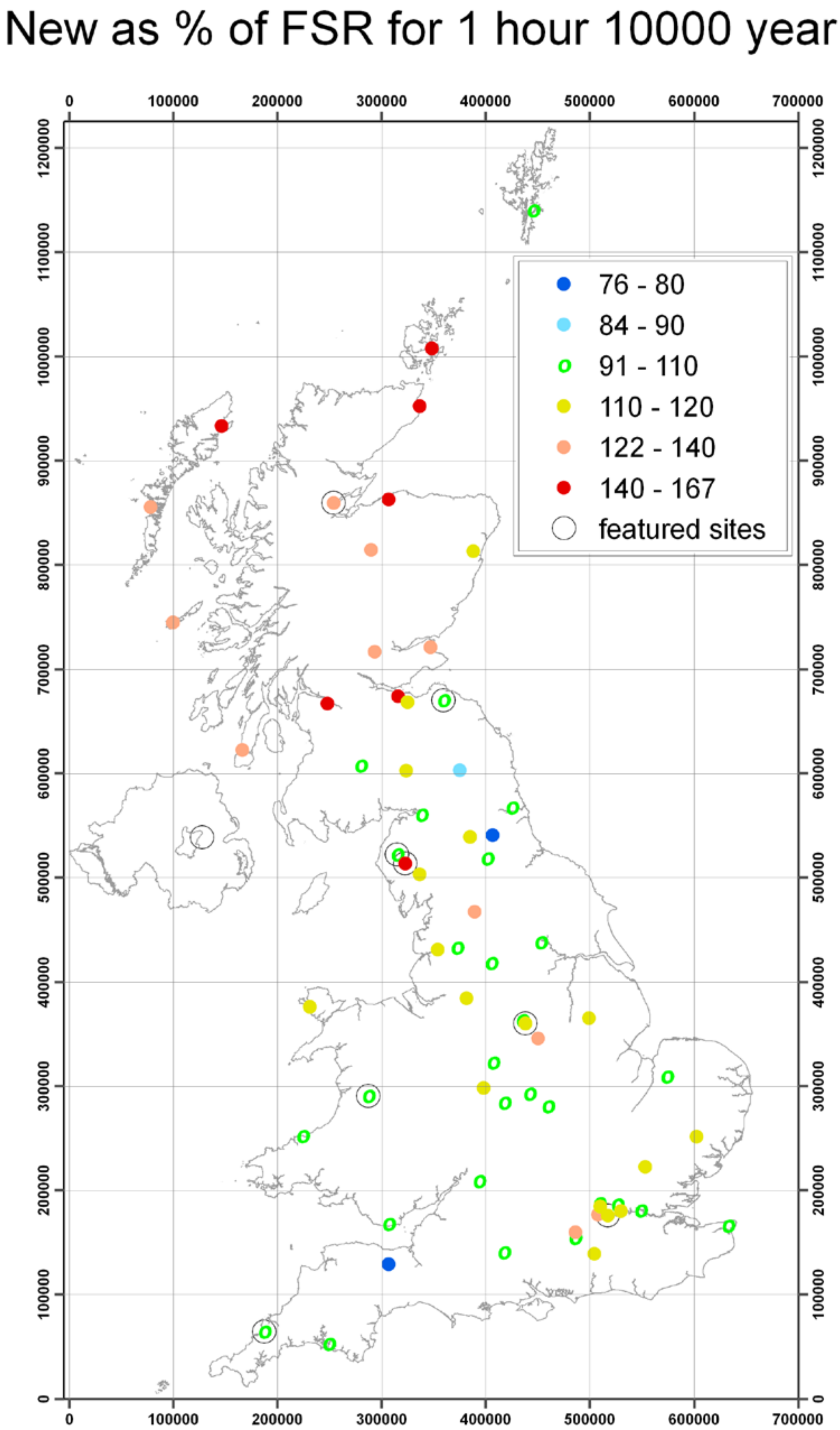

Figure 9.4 New rainfall estimates compared with FSR for 1-hour duration, 10,000-year return period

New as % of FEH for 6 hour 150 year

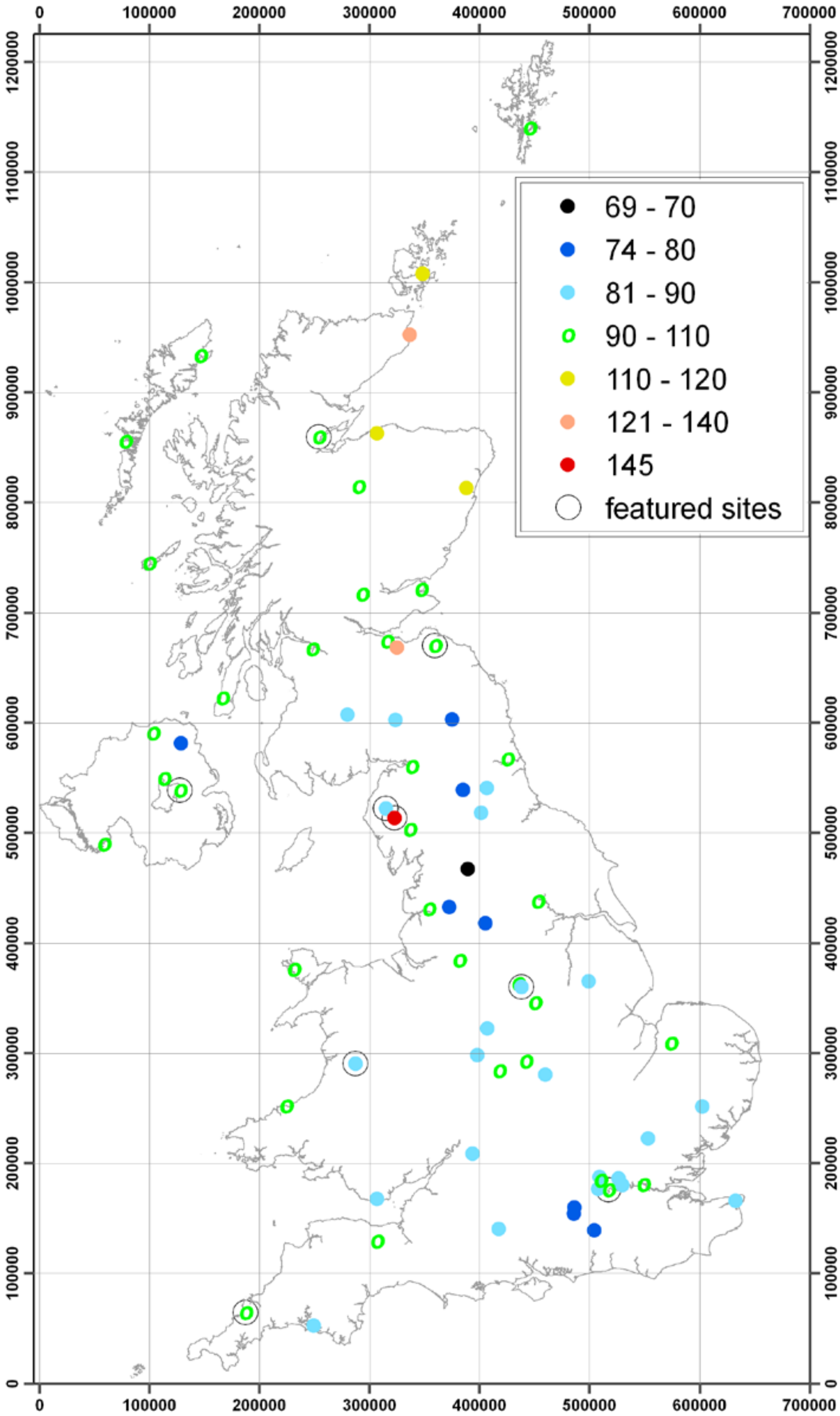

Figure 9.5 New rainfall estimates compared with FEH for 6-hour duration, 150-year return period

New as % of FSR for 6 hour 150 year

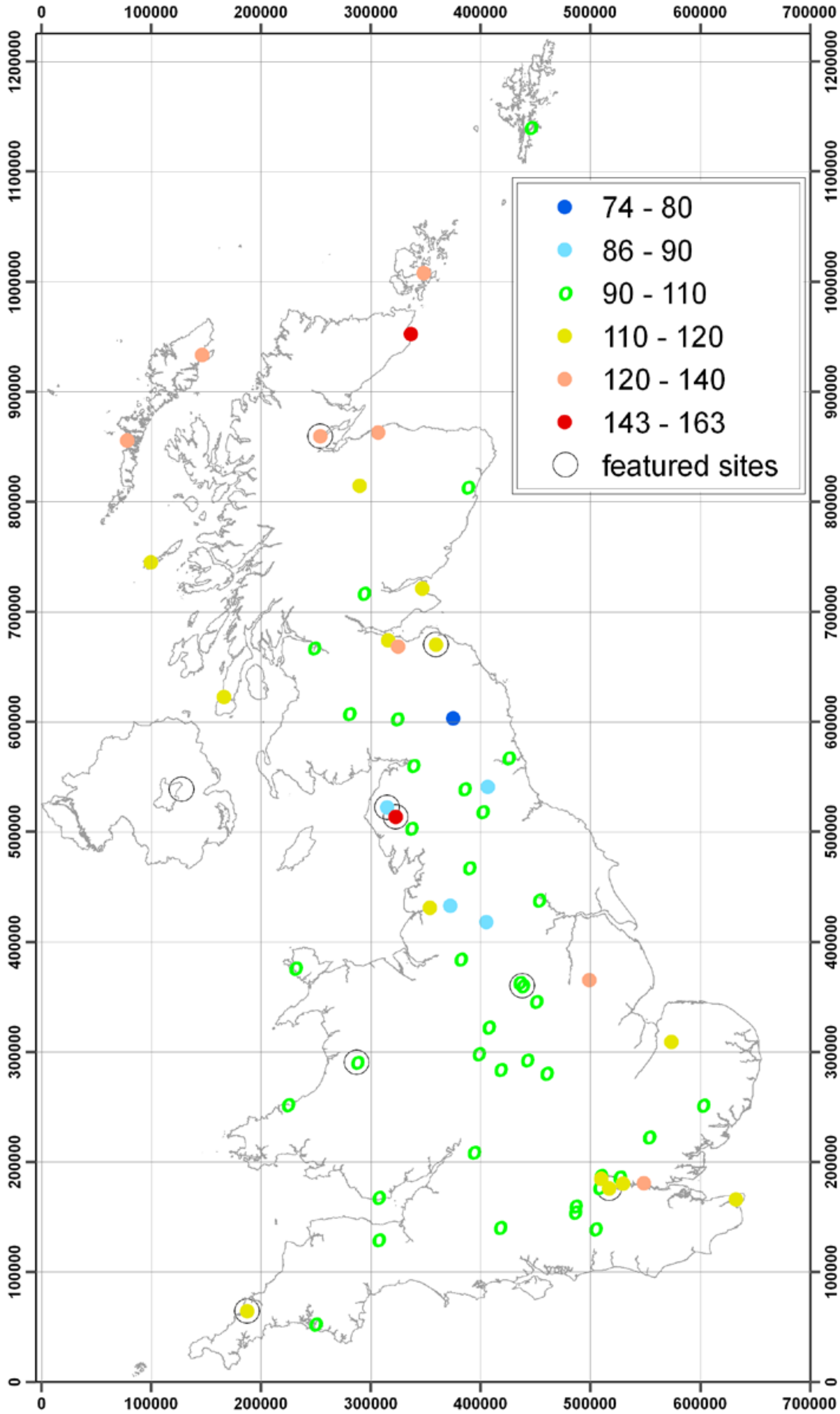

Figure 9.6 New rainfall estimates compared with FSR for 6-hour duration, 150-year return period

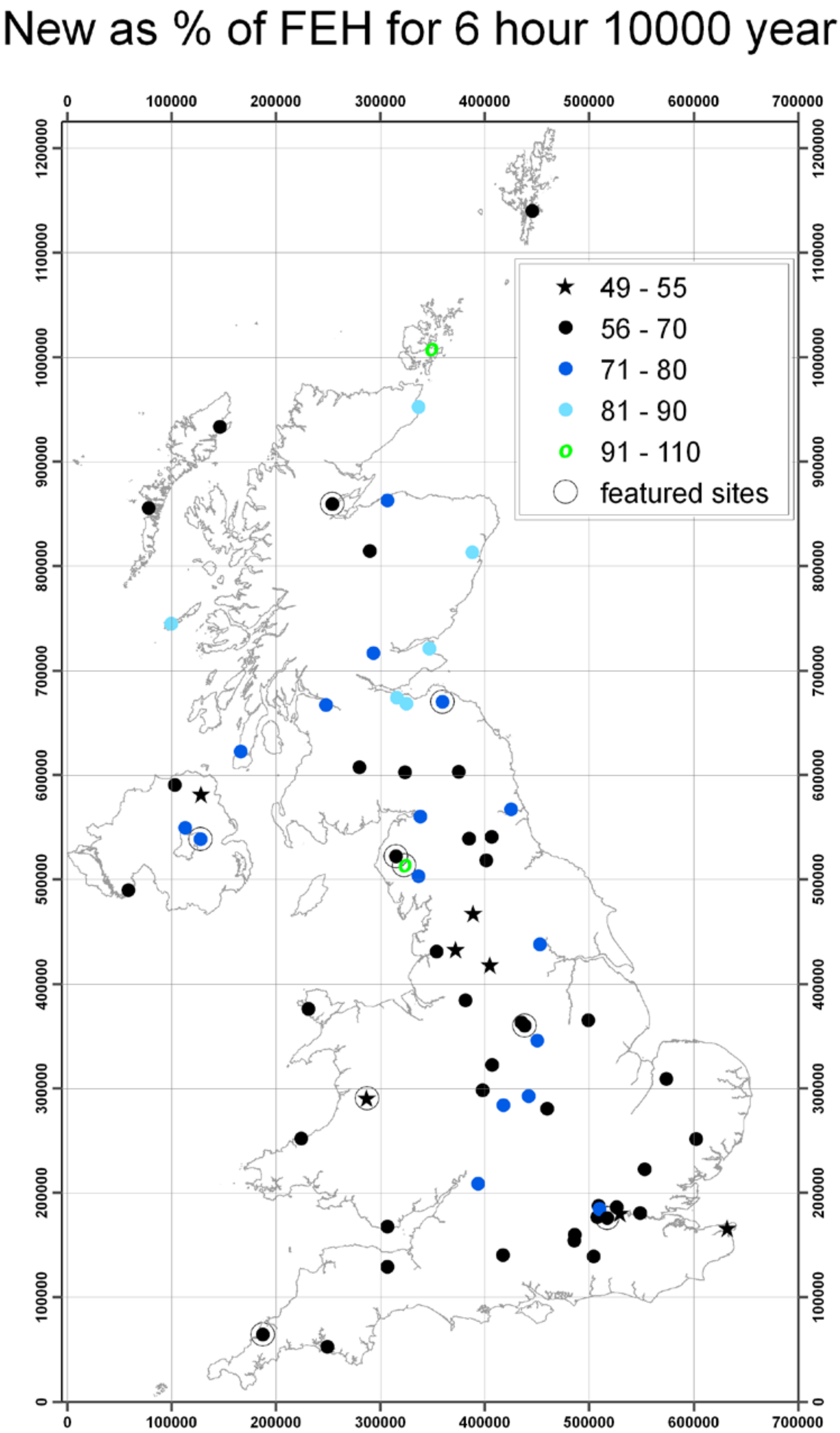

Figure 9.7 New rainfall estimates compared with FEH for 6-hour duration, 10,000-year return period

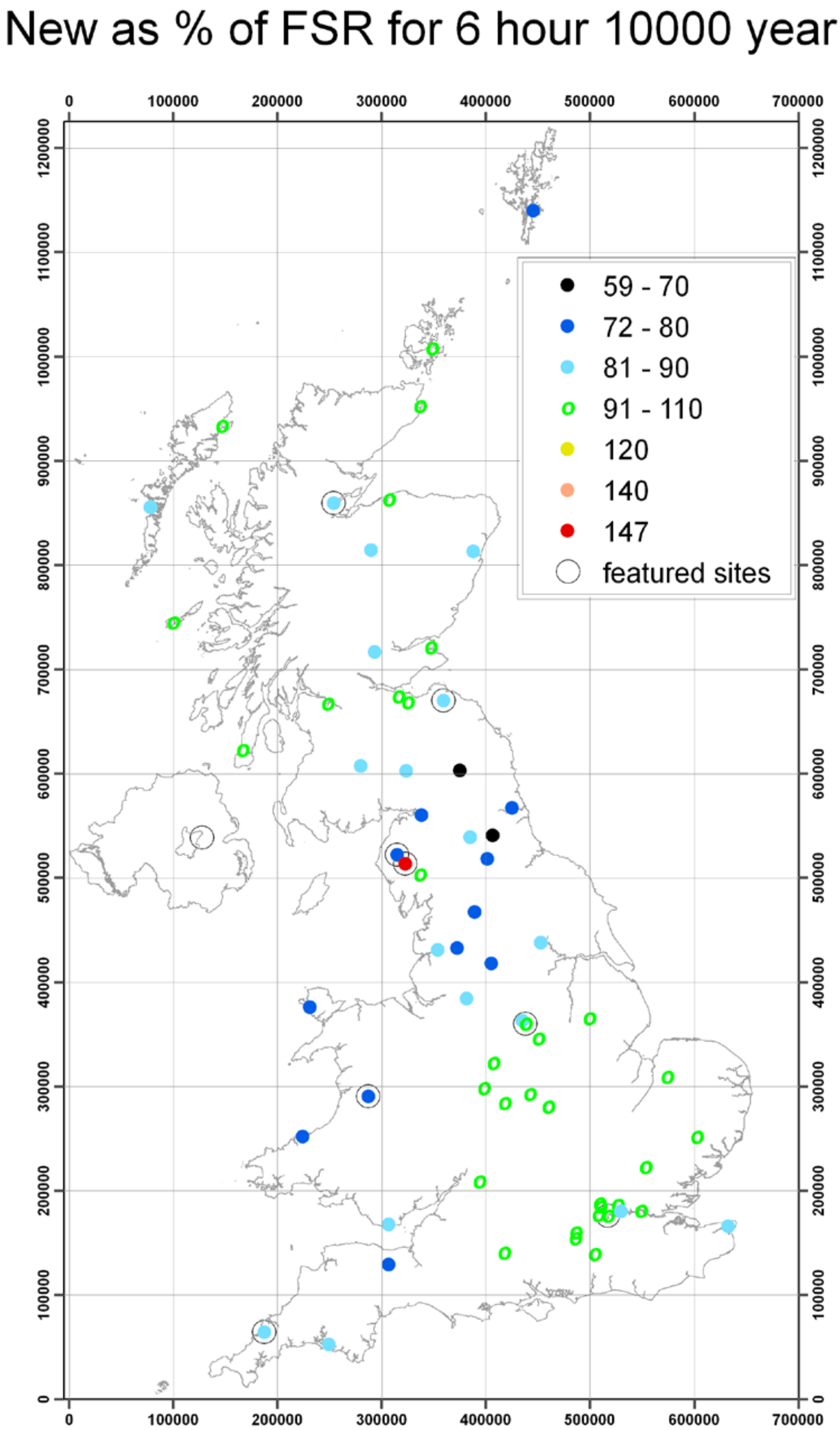

Figure 9.8 New rainfall estimates compared with FSR for 6-hour duration, 10,000-year return period

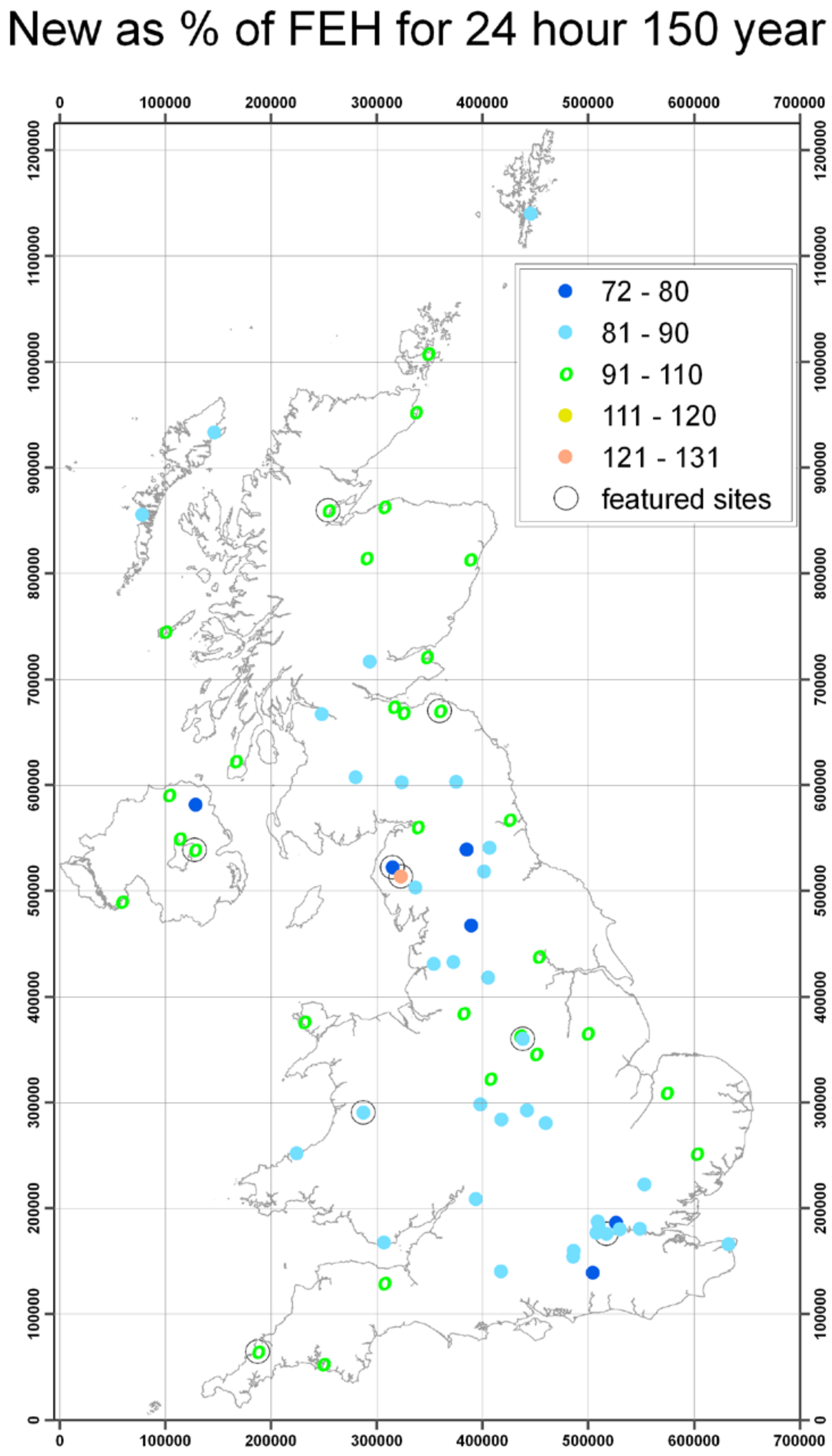

Figure 9.9 New rainfall estimates compared with FEH for 24-hour duration, 150-year return period

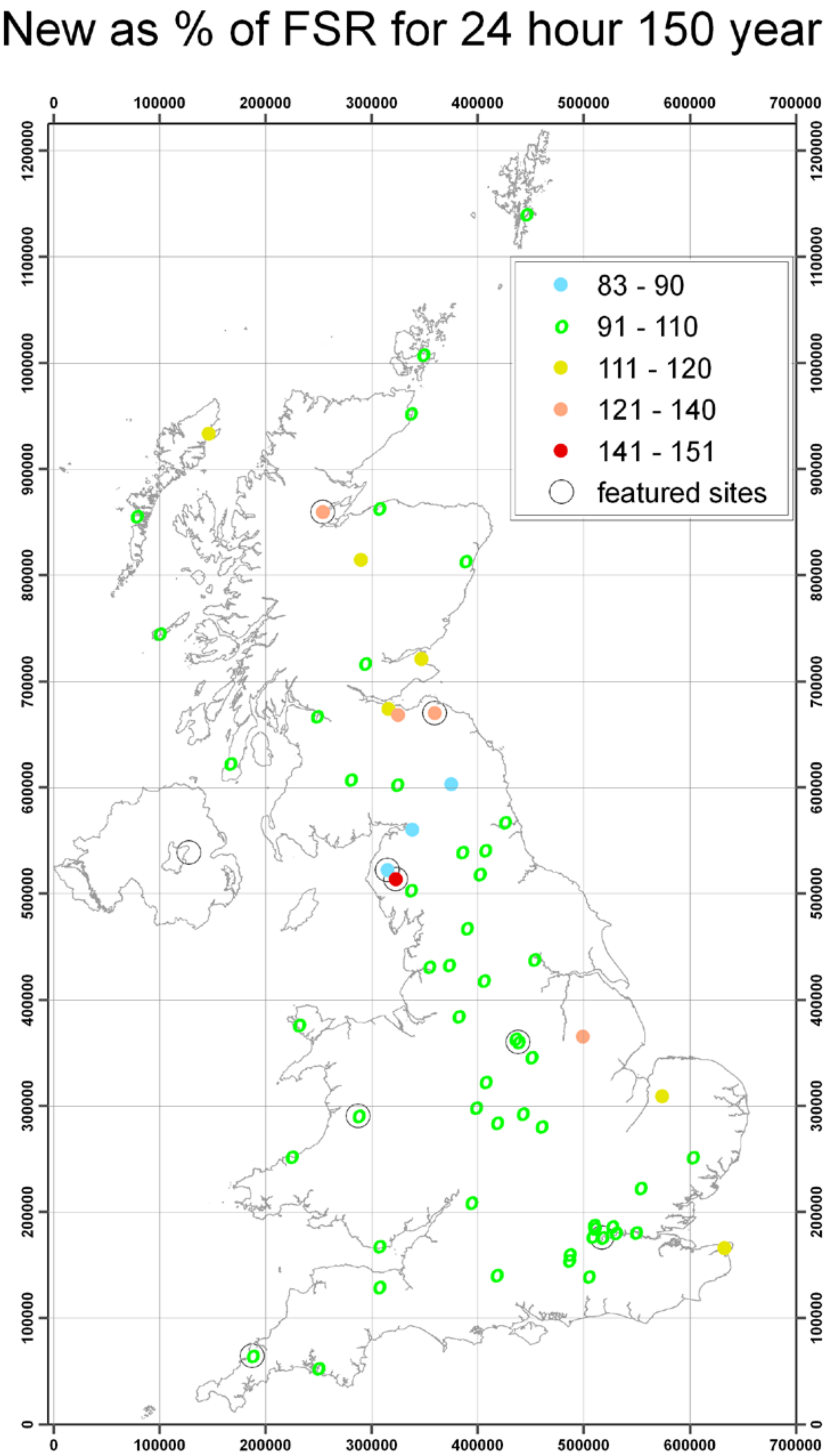

Figure 9.10 New rainfall estimates compared with FSR for 24-hour duration, 150-year return period

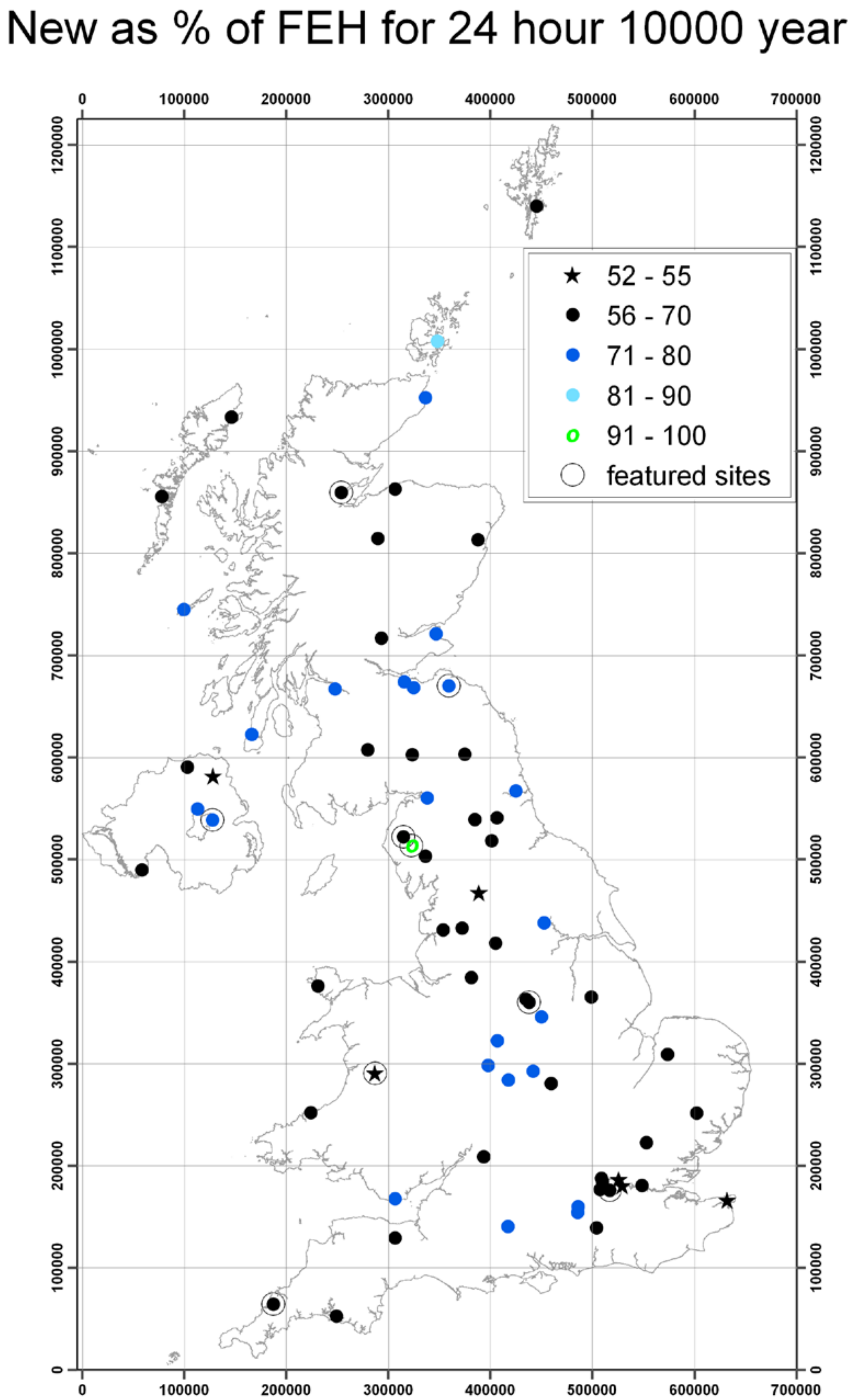

Figure 9.11 New rainfall estimates compared with FEH for 24-hour duration, 10,000-year return period

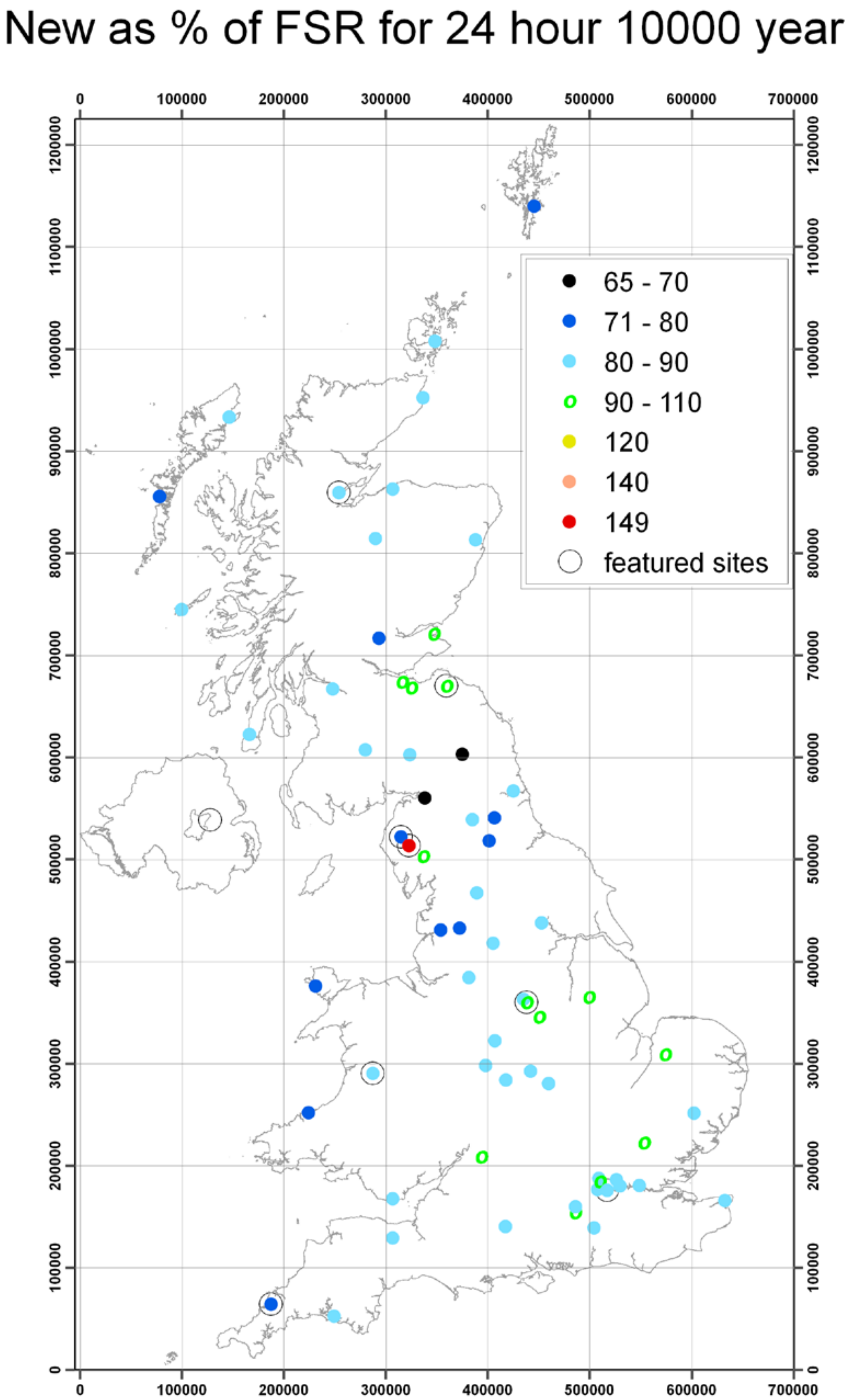

Figure 9.12 New rainfall estimates compared with FSR for 24-hour duration, 10,000-year return period

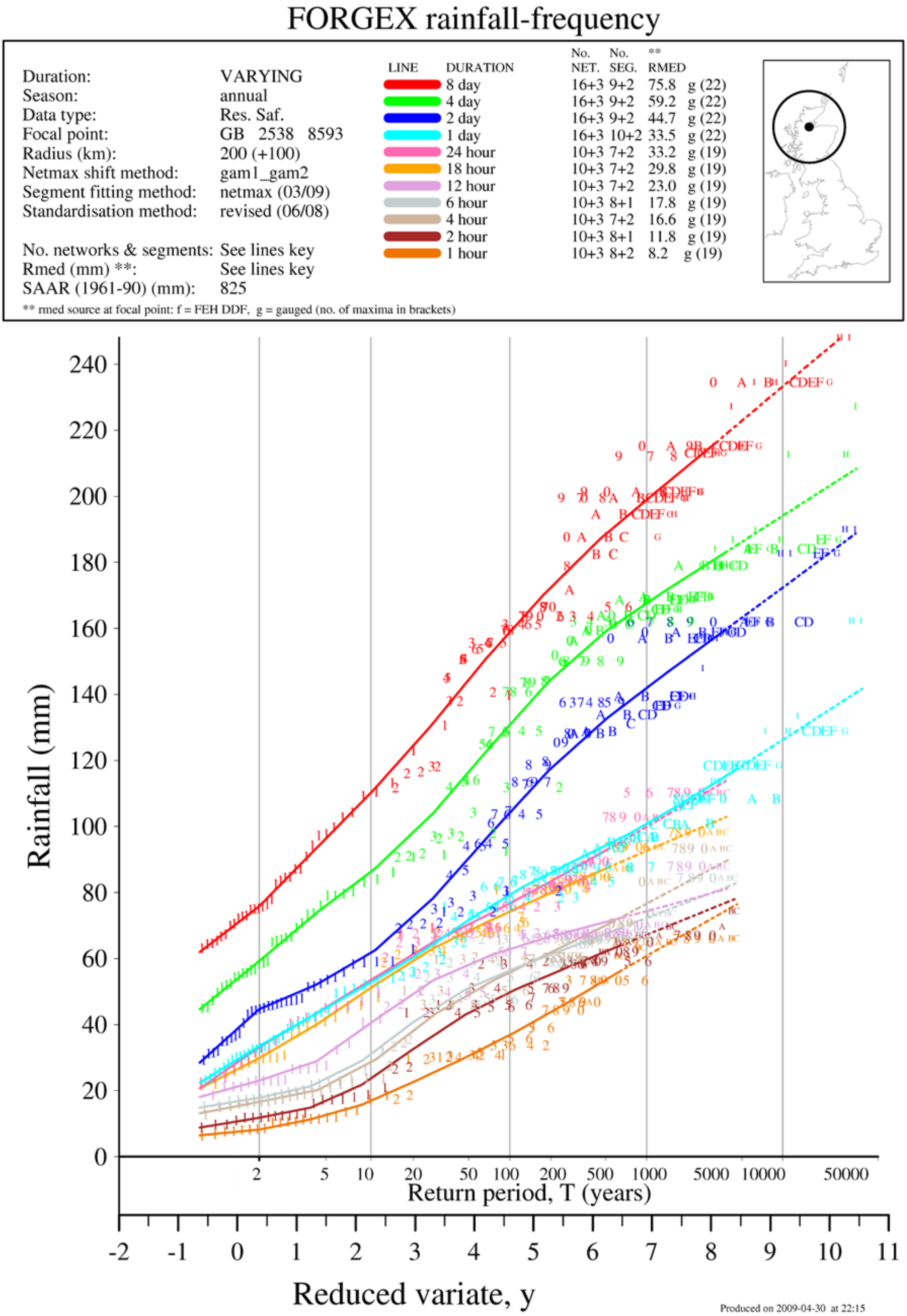

Figure 9.13 FORGEX rainfall frequency plots for Dingwall

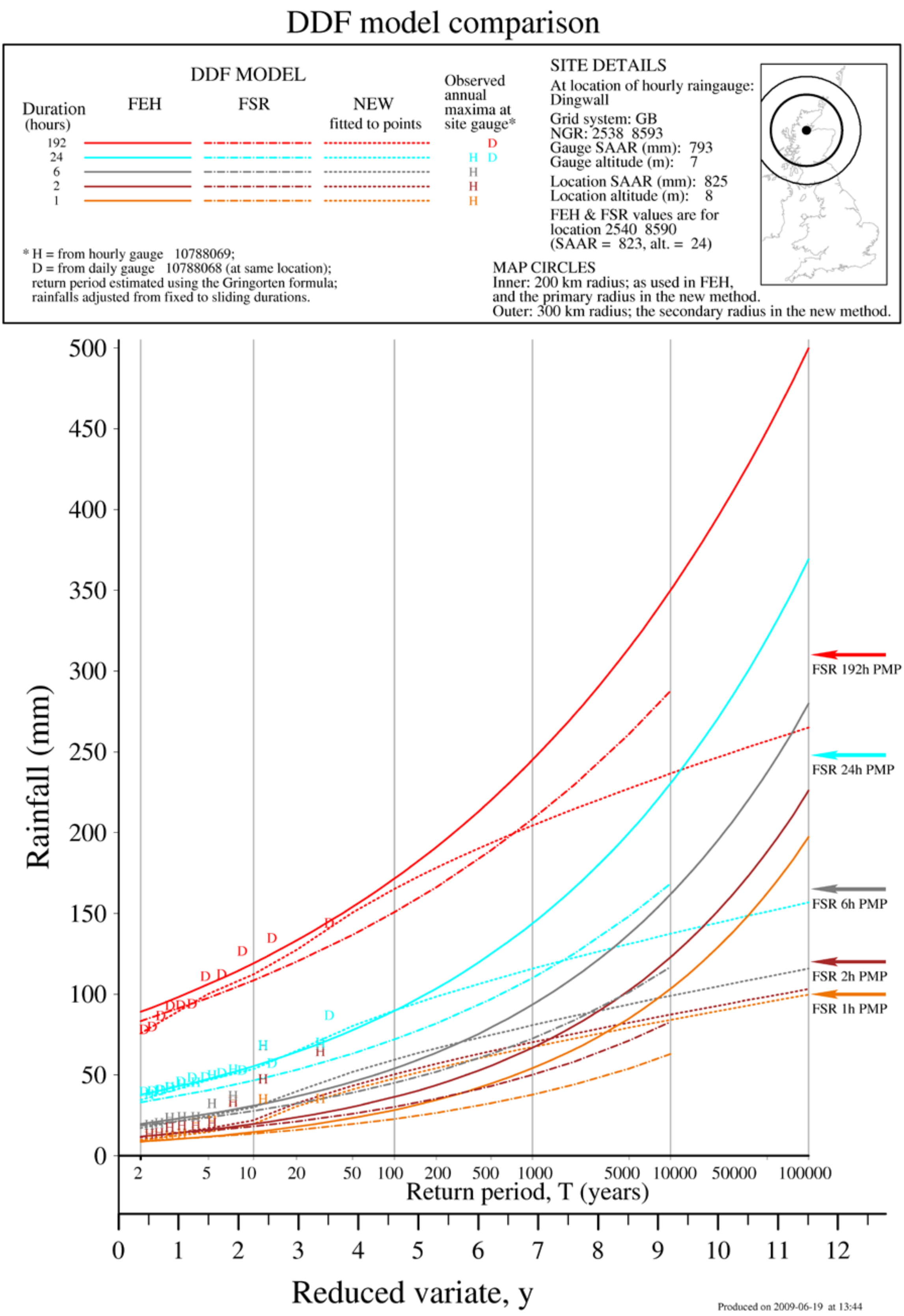

Figure 9.14 Comparison of DDF models for Dingwall

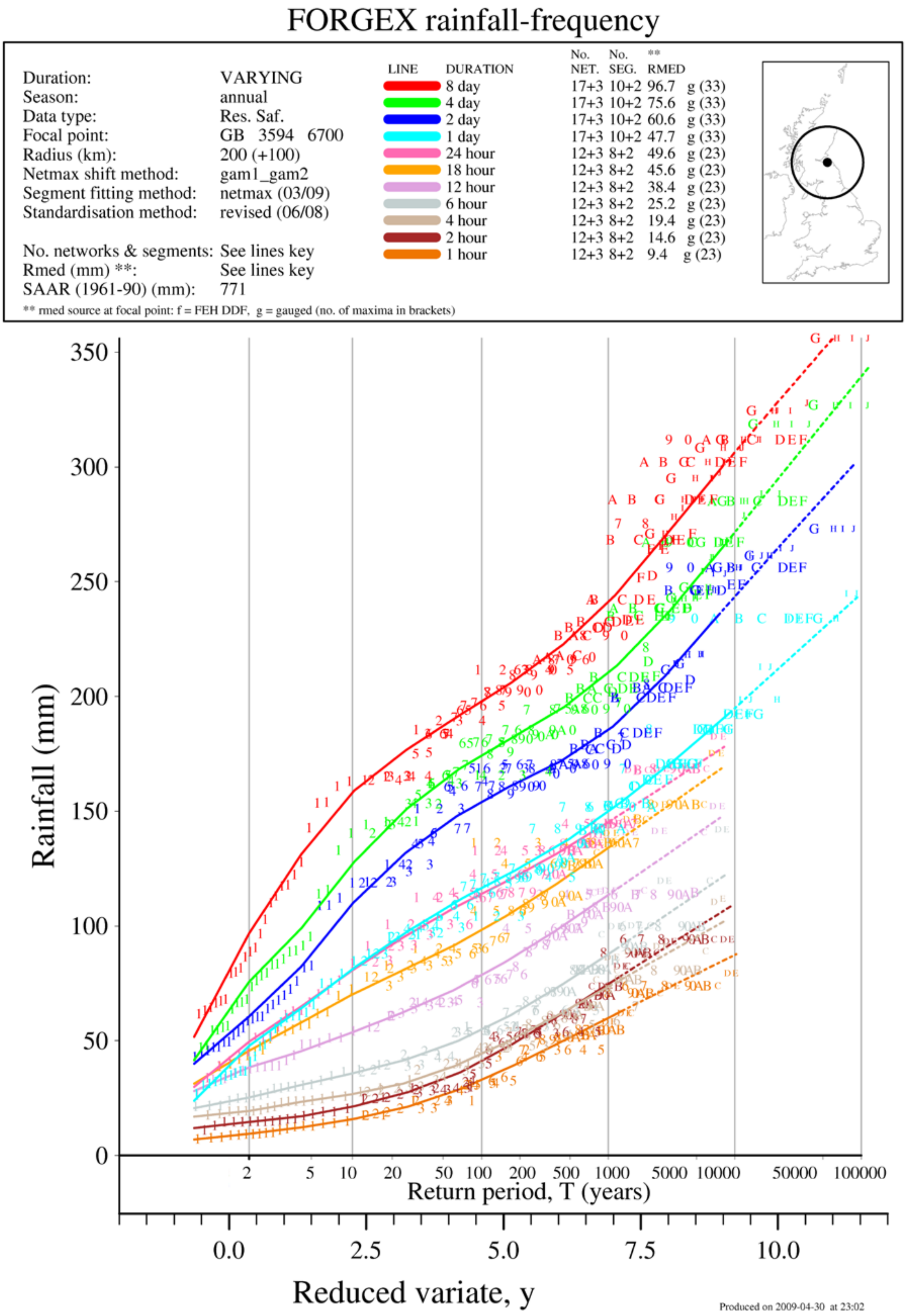

Figure 9.15 FORGEX rainfall frequency plots for Nunraw Abbey

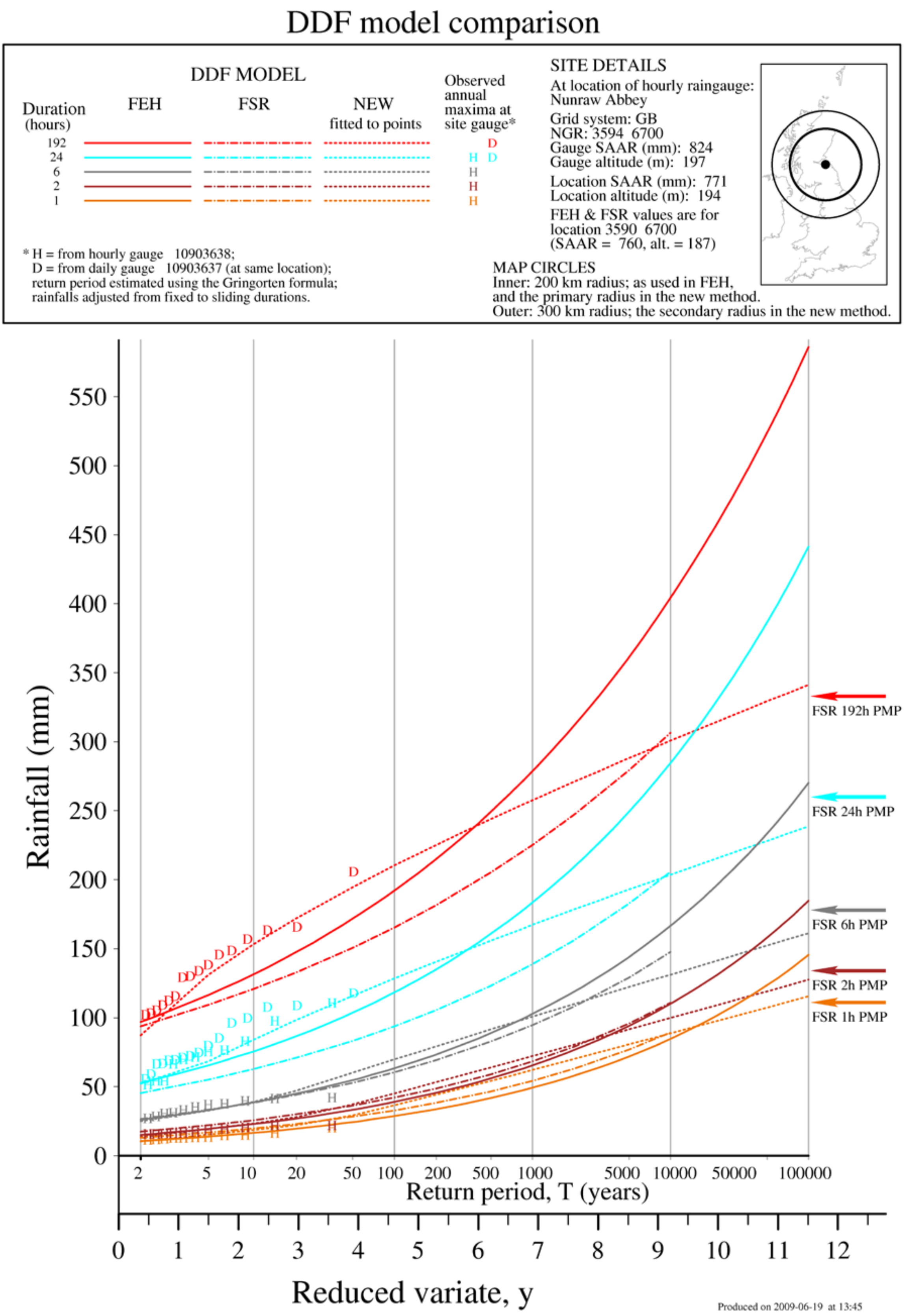

Figure 9.16 Comparison of DDF models for Nunraw Abbey

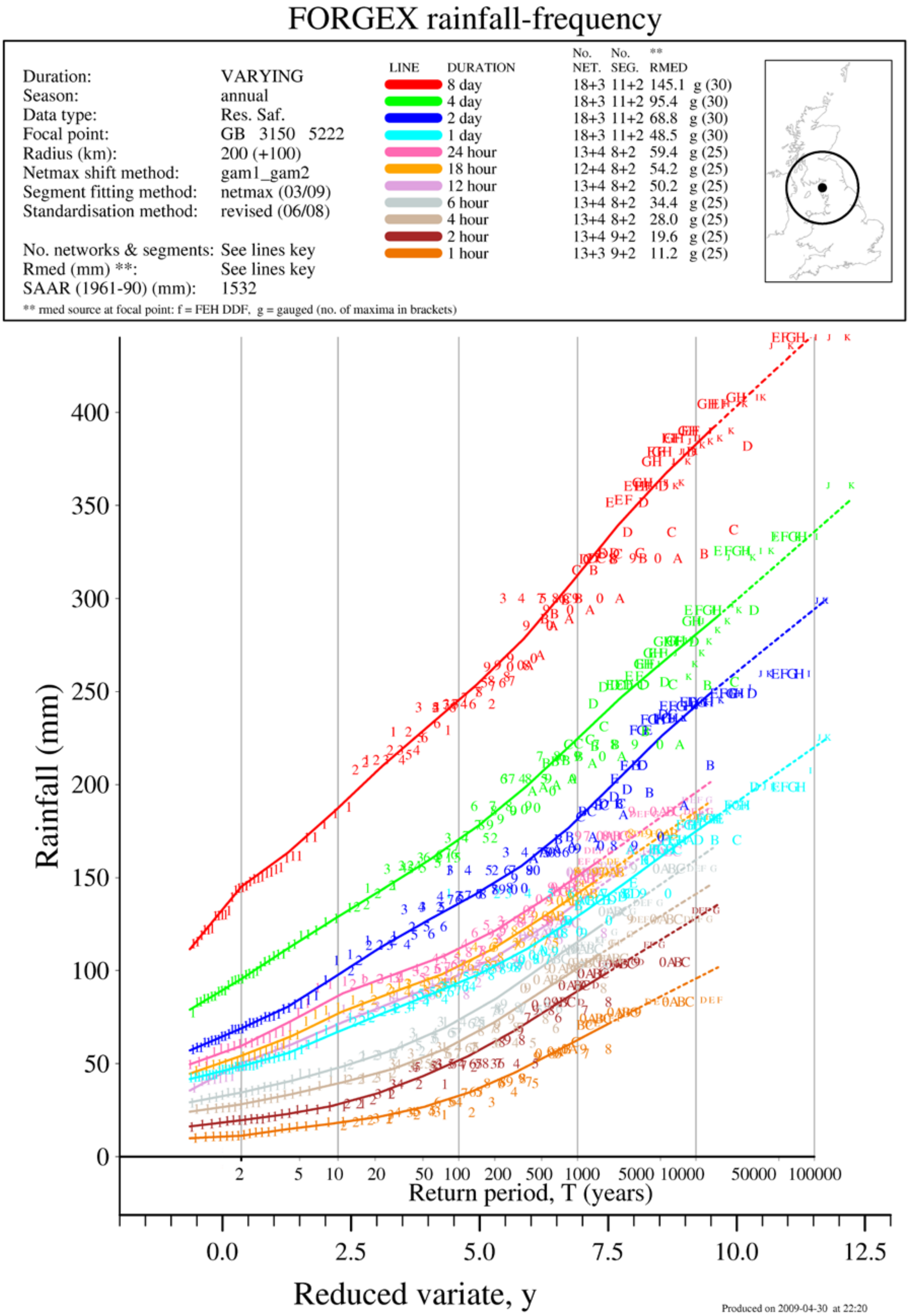

Figure 9.17 FORGEX rainfall frequency plots for Cornhow

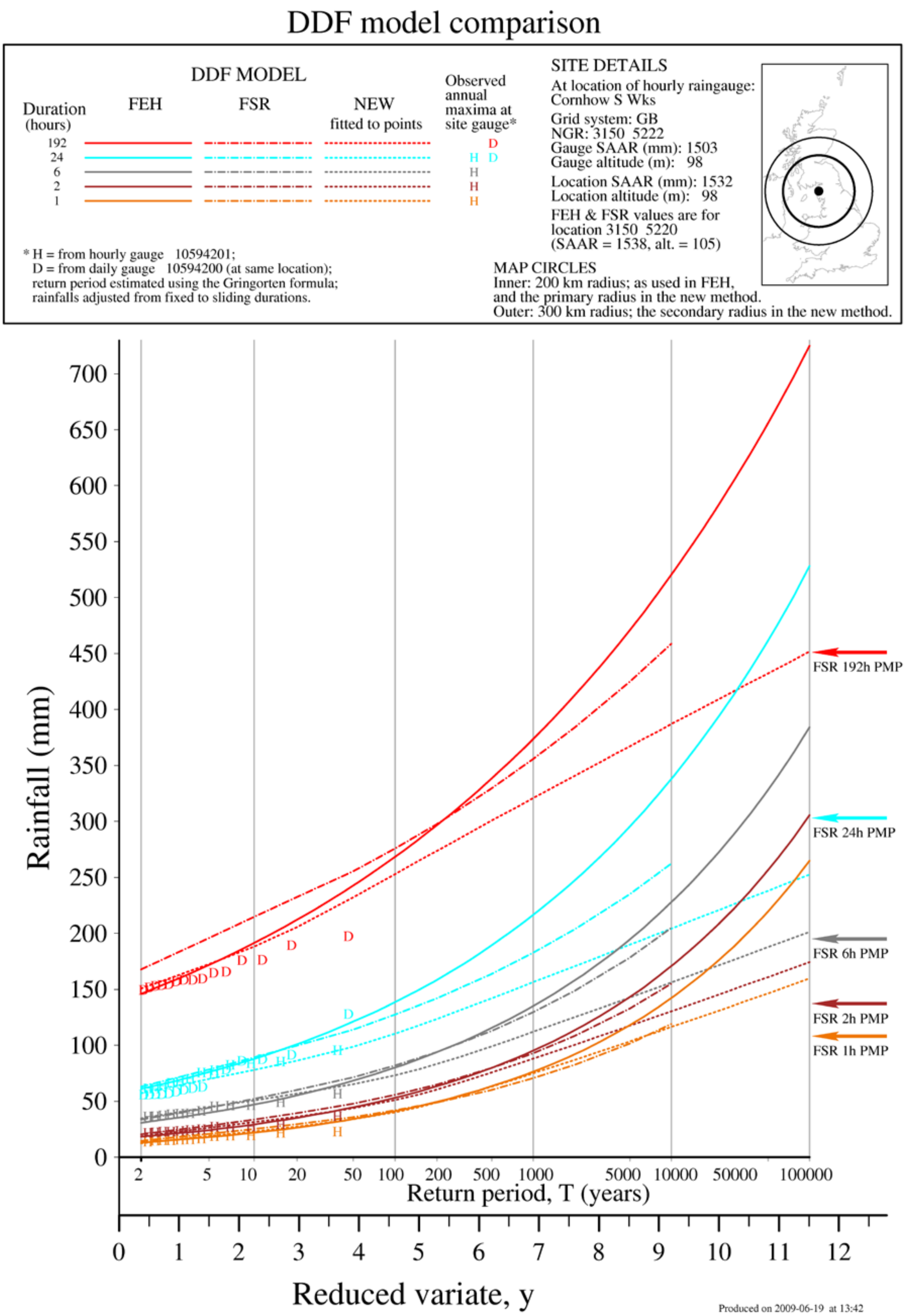

Figure 9.18 Comparison of DDF models for Cornhow

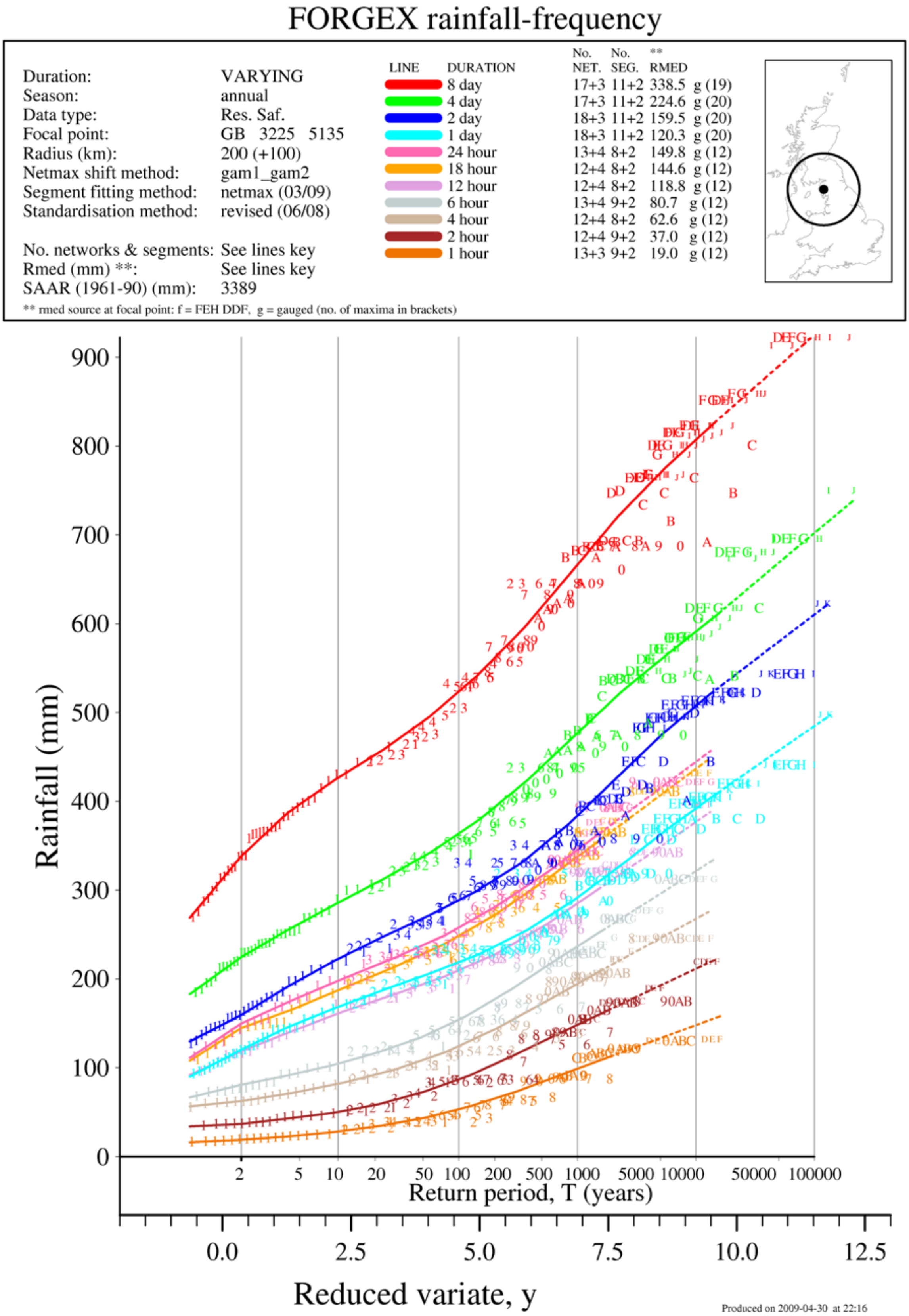

Figure 9.19 **FORGEX rainfall frequency plots for Honister Pass**

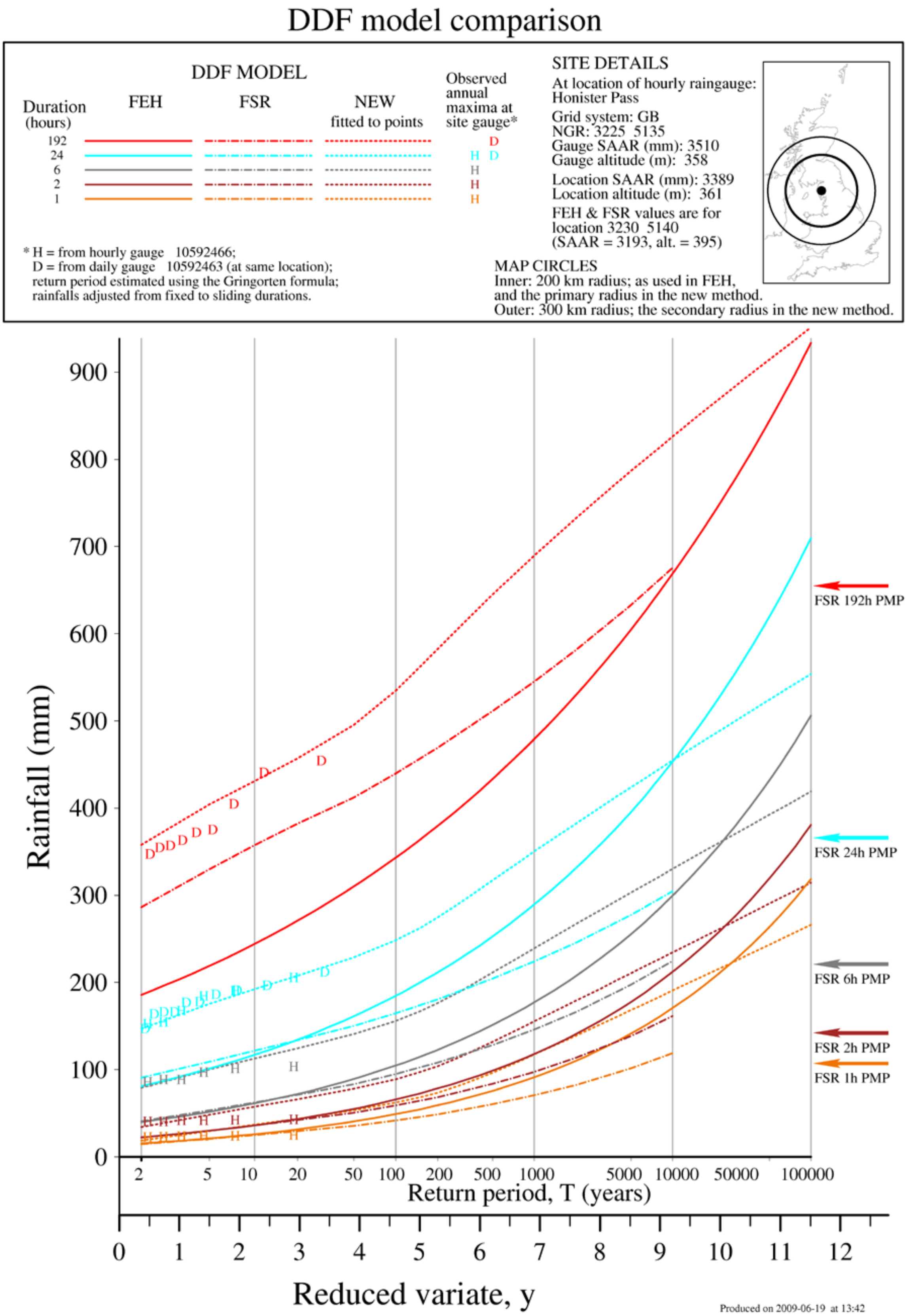

Figure 9.20 Comparison of DDF models for Honister Pass

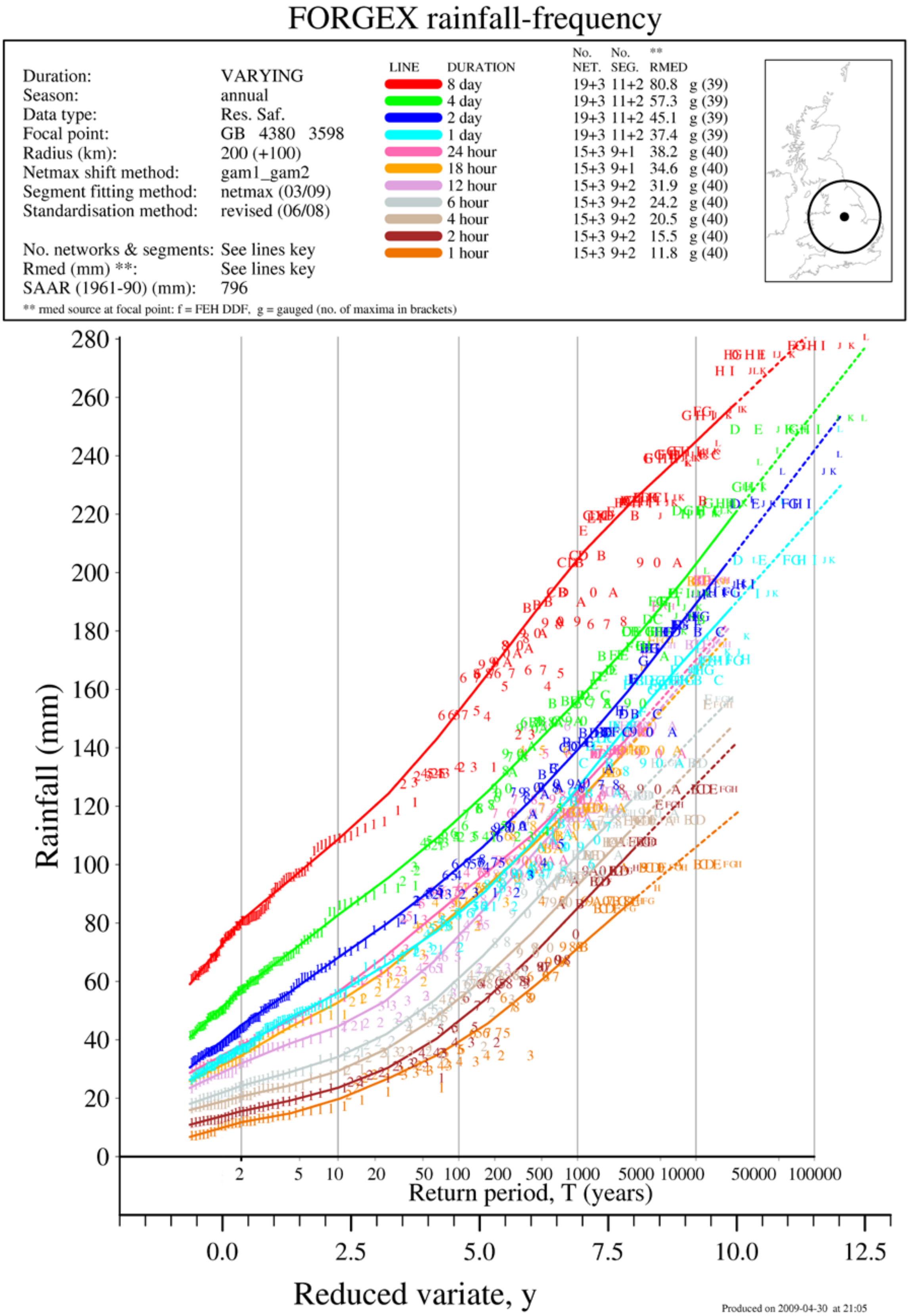

Figure 9.21 FORGEX rainfall frequency plots for Ogston Reservoir

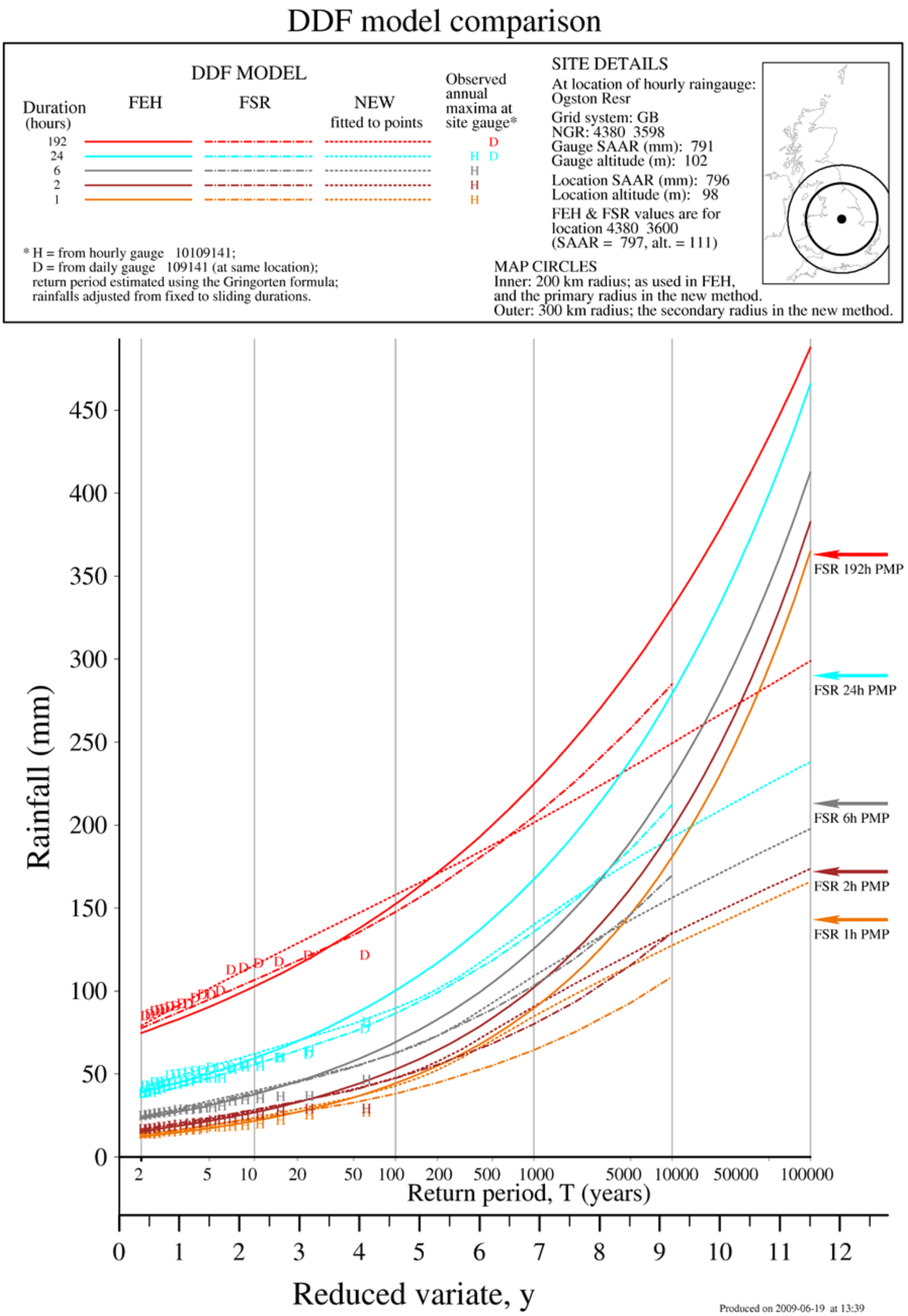

Figure 9.22 Comparison of DDF models for Ogston Reservoir

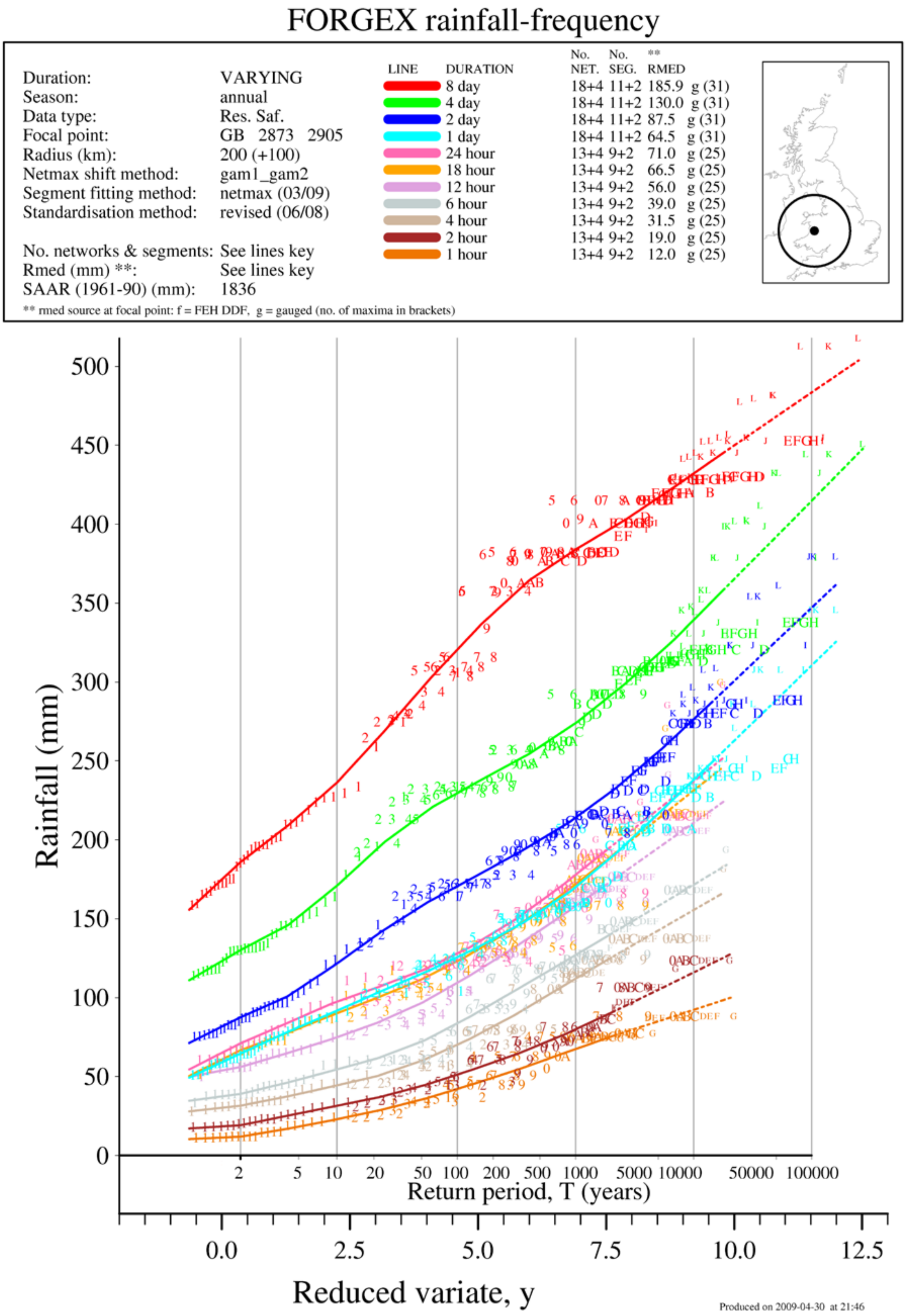

Figure 9.23 FORGEX rainfall frequency plots for Dolydd

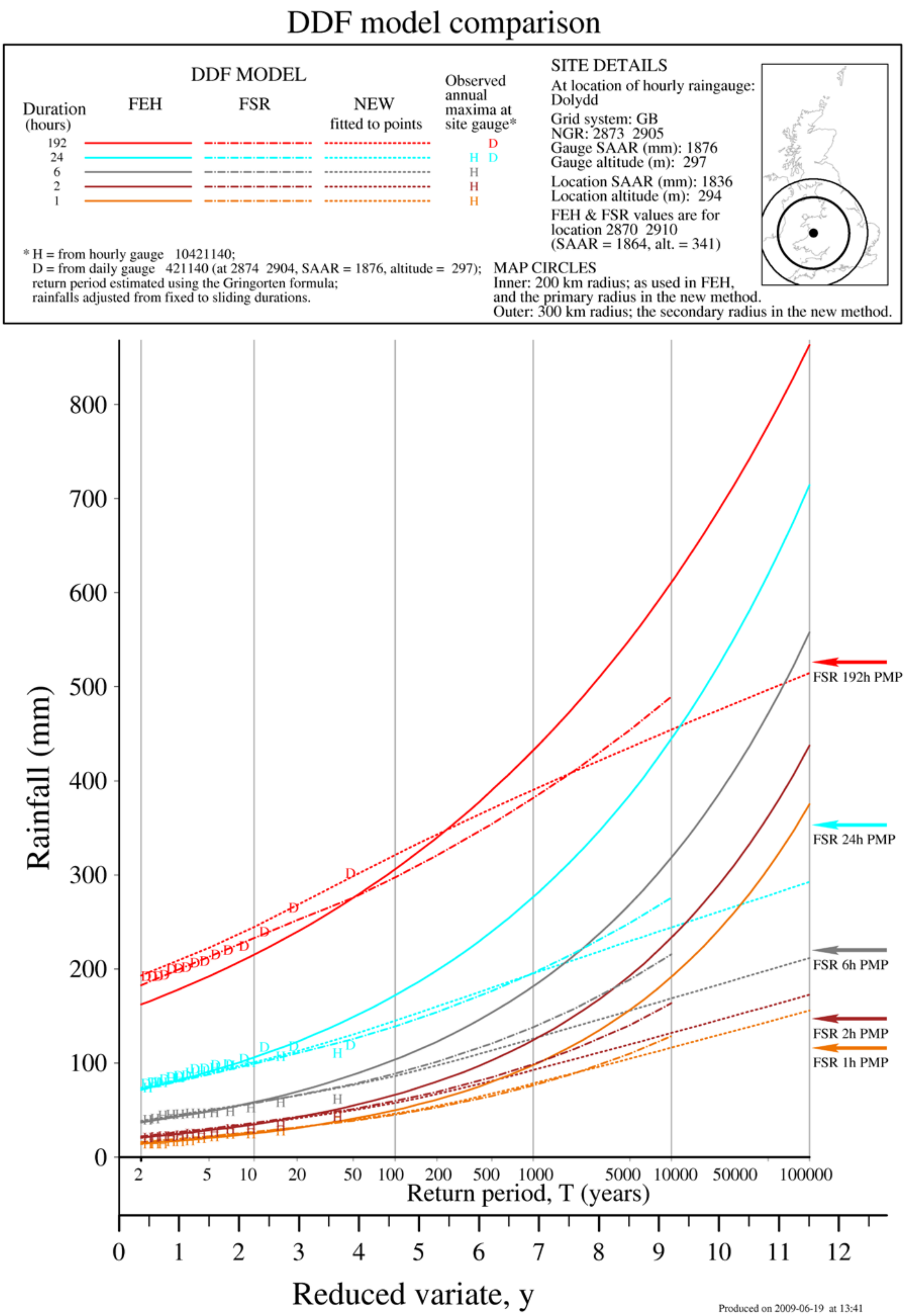

Figure 9.24 Comparison of DDF models for Dolydd

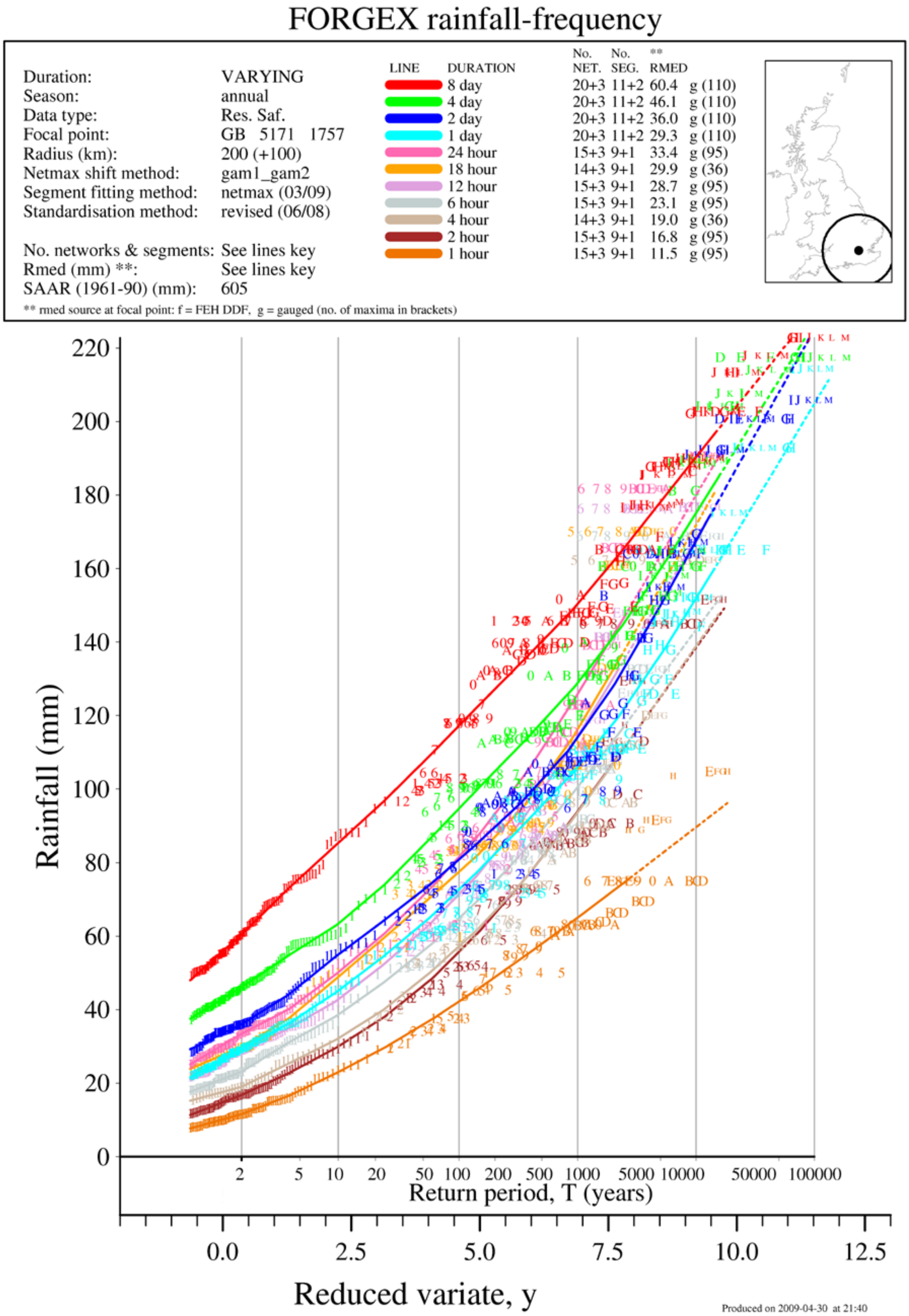

Figure 9.25 FORGEX rainfall frequency plots for Kew

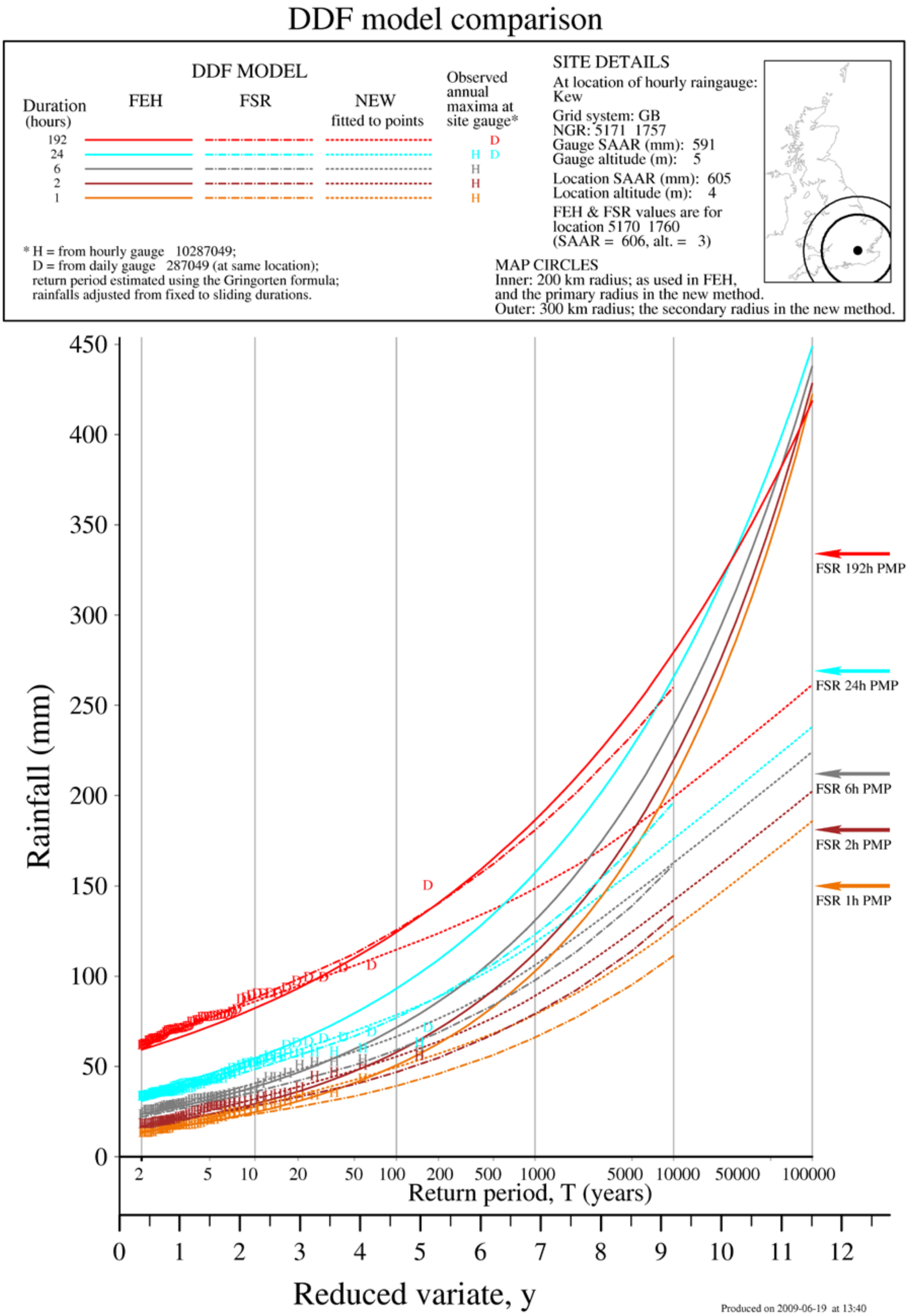

Figure 9.26 Comparison of DDF models for Kew

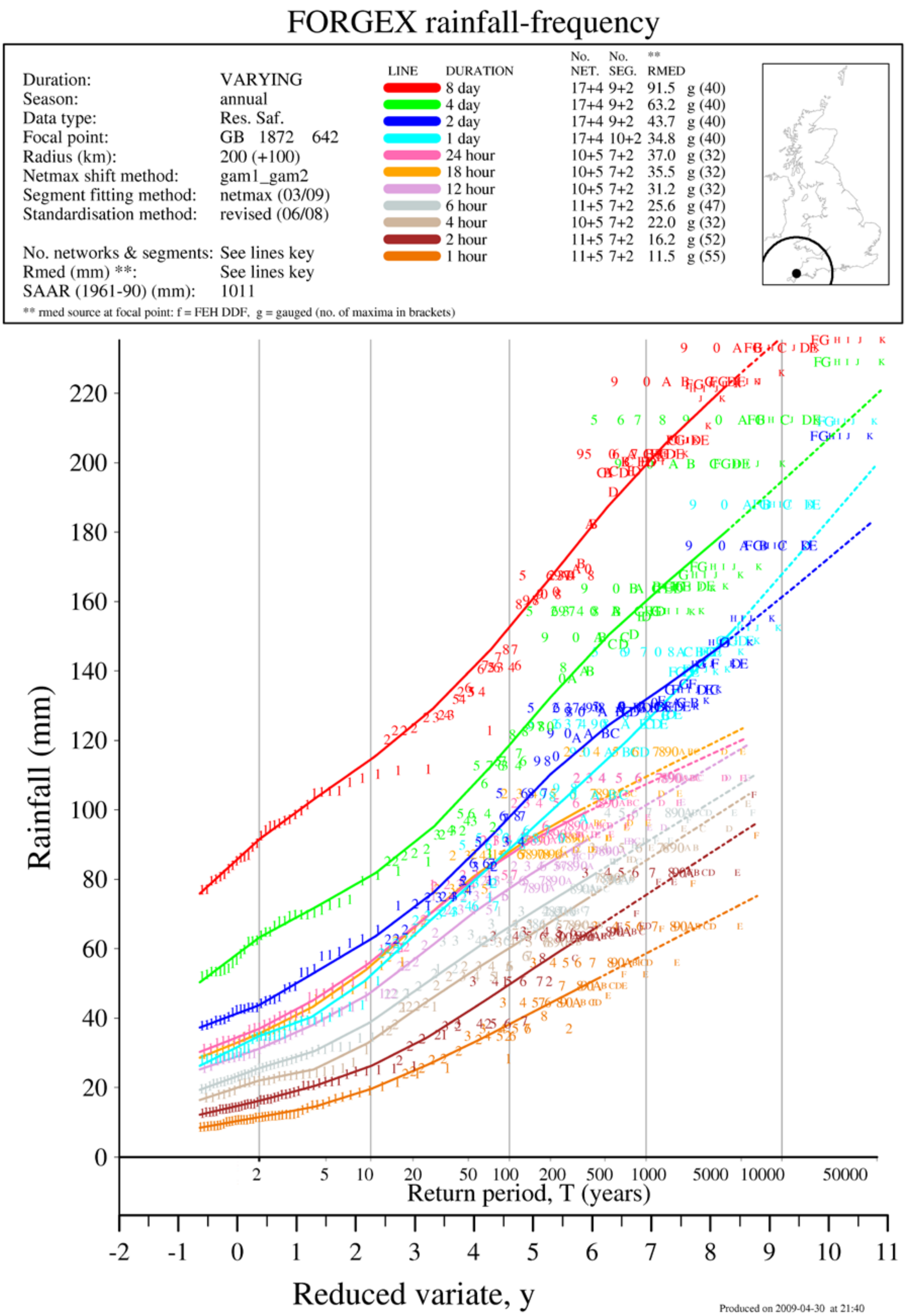

Figure 9.27 FORGEX rainfall frequency plots for St Mawgan

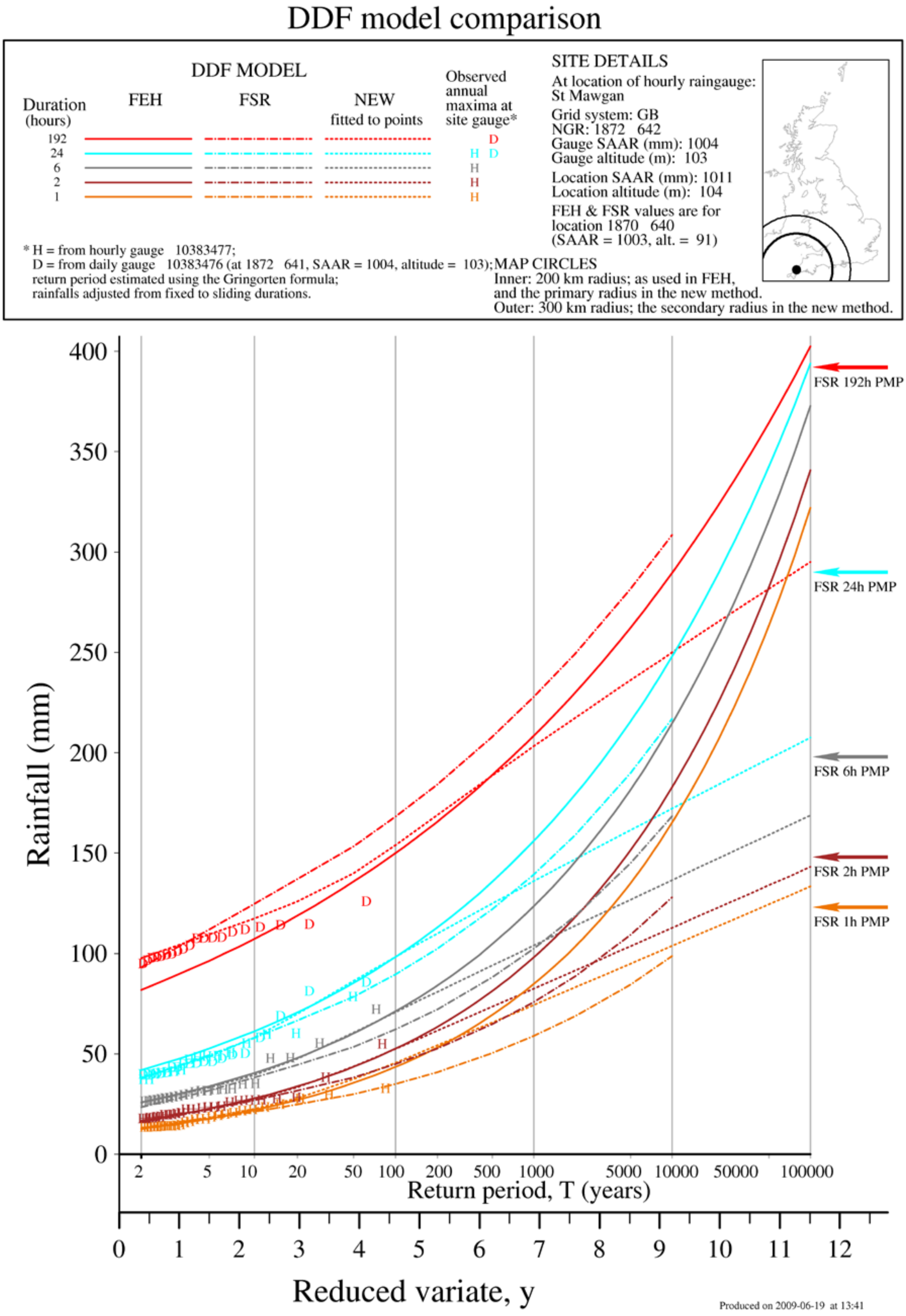

Figure 9.28 Comparison of DDF models for St Mawgan

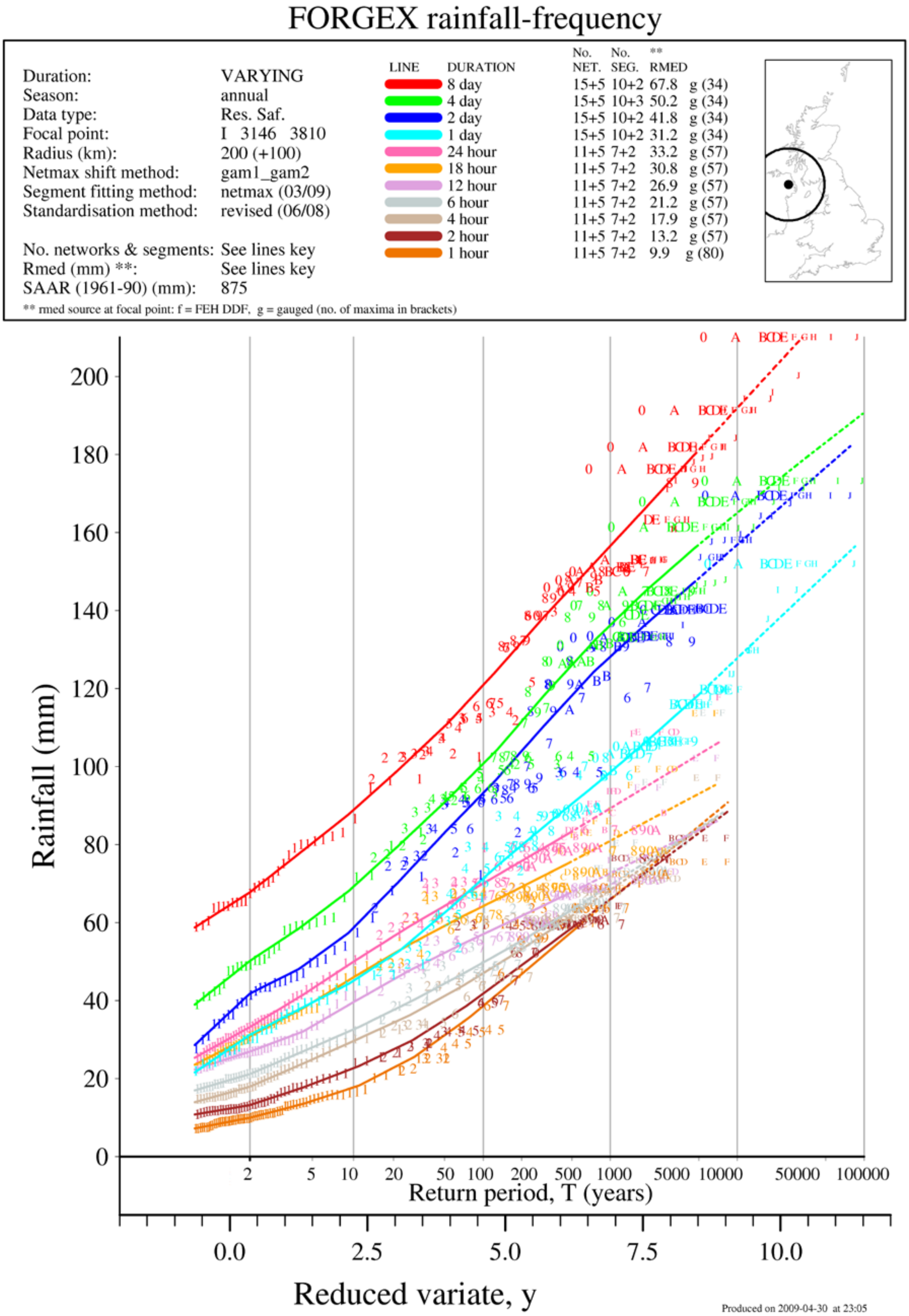

Figure 9.29 FORGEX rainfall frequency plots for Aldergrove

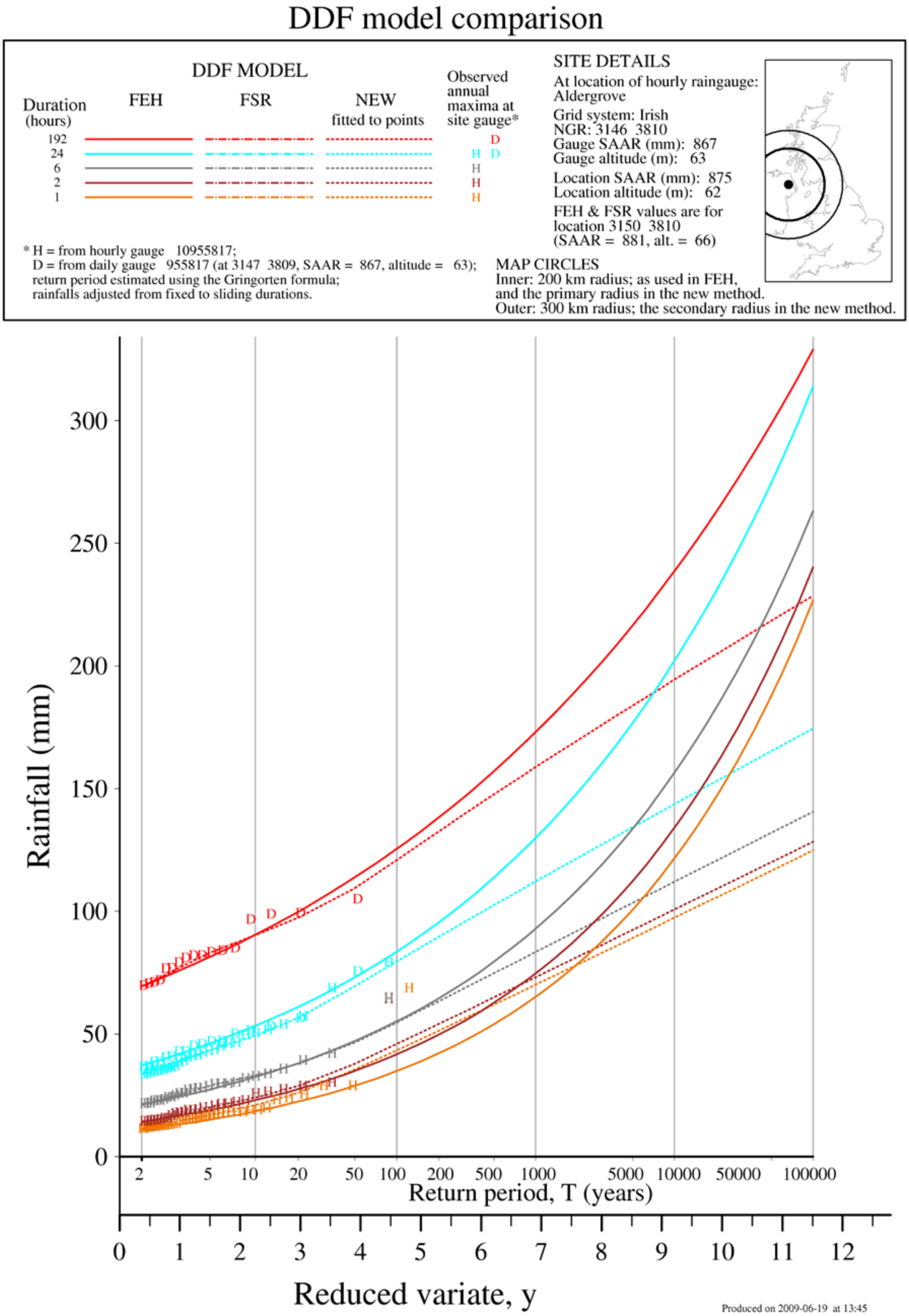

Figure 9.30 Comparison of DDF models for Aldergrove

Table 9.2 Rainfall comparisons for Dingwall

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	25	32	52	207	163	25	32	52
1	200	27	34	54	204	157	27	34	54
1	1000	38	54	67	178	124	38	54	67
1	10000	63	103	84	134	81	63	103	84
1	100000	(PMP: 100)		100					100
6	150	49	59	64	130	107	30	36	39
6	200	52	64	66	128	104	31	39	40
6	1000	73	93	81	111	86	44	57	49
6	10000	117	162	99	85	61	71	98	60
6	100000	(PMP: 165)		116					70
24	150	78	97	95	122	97	31	39	38
24	200	82	103	98	120	95	33	42	40
24	1000	110	144	116	105	80	44	58	47
24	10000	168	230	137	82	60	68	93	55
24	100000	(PMP: 248)		157					63
192	150	160	183	173	108	95	51	59	56
192	200	166	191	178	107	93	54	62	57
192	1000	208	245	204	98	83	67	79	66
192	10000	288	350	237	82	68	93	113	76
192	100000	(PMP: 310)		265					86

Table 9.3 Rainfall comparisons for Nunraw Abbey

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	36	32	41	114	130	32	28	37
1	200	38	34	44	116	131	34	30	40
1	1000	54	49	62	115	126	49	44	56
1	10000	89	85	89	99	105	81	76	80
1	100000	(PMP: 111)		116					104
6	150	65	69	75	115	109	37	39	42
6	200	69	73	79	114	108	39	41	44
6	1000	95	103	101	107	98	53	58	57
6	10000	148	167	131	89	79	83	94	74
6	100000	(PMP: 178)		161					91
24	150	100	128	135	135	106	39	49	52
24	200	105	135	140	133	104	41	52	54
24	1000	139	184	167	121	91	53	71	64
24	10000	206	285	204	99	72	79	109	78
24	100000	(PMP: 260)		239					92
192	150	175	205	219	125	107	52	62	66
192	200	182	215	225	124	105	55	65	68
192	1000	225	279	258	114	92	68	84	77
192	10000	307	404	301	98	74	92	121	90
192	100000	(PMP: 333)		341					102

Table 9.4 Rainfall comparisons for Cornhow

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	46	46	45	98	98	42	42	41
1	200	49	49	49	99	98	45	46	45
1	1000	70	76	75	106	98	65	71	69
1	10000	119	142	116	98	82	110	132	108
1	100000	(PMP: 108)		160					148
6	150	89	88	79	89	90	46	45	40
6	200	94	94	83	88	89	48	48	43
6	1000	130	135	112	86	83	66	69	57
6	10000	205	228	156	76	69	105	117	80
6	100000	(PMP: 195)		202					103
24	150	136	150	118	87	79	45	49	39
24	200	142	158	123	87	78	47	52	41
24	1000	183	216	156	86	72	60	71	52
24	10000	262	338	204	78	60	87	112	67
24	100000	(PMP: 303)		253					83
192	150	288	284	265	92	93	64	63	59
192	200	298	296	274	92	92	66	66	61
192	1000	356	374	321	90	86	79	83	71
192	10000	459	520	387	84	74	102	115	86
192	100000	(PMP: 451)		451					100

Table 9.5 Rainfall comparisons for Honister Pass

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	46	55	68	149	125	43	51	64
1	200	49	59	74	151	125	46	55	69
1	1000	70	91	117	167	128	66	85	110
1	10000	119	171	191	160	112	111	159	178
1	100000	(PMP: 107)		267					249
6	150	102	115	167	163	145	46	52	75
6	200	108	123	176	163	143	49	55	80
6	1000	146	177	239	164	135	66	80	108
6	10000	225	299	330	147	110	102	135	149
6	100000	(PMP: 221)		419					190
24	150	174	200	263	151	131	48	55	72
24	200	181	211	274	152	130	49	58	75
24	1000	224	289	350	156	121	61	79	96
24	10000	304	453	455	149	100	83	124	124
24	100000	(PMP: 366)		554					151
192	150	457	364	562	123	154	70	56	86
192	200	469	379	582	124	153	72	58	89
192	1000	545	479	689	126	144	83	73	105
192	10000	675	669	826	122	124	103	102	126
192	100000	(PMP: 655)		951					145

Table 9.6 Rainfall comparisons for Ogston Reservoir

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	42	50	48	114	95	29	35	33
1	200	45	55	52	117	95	31	38	36
1	1000	64	90	85	132	95	45	63	59
1	10000	108	181	127	117	70	76	126	89
1	100000	(PMP: 143)		165					116
6	150	69	77	68	99	88	32	36	32
6	200	73	83	73	100	88	34	39	34
6	1000	103	125	109	106	87	48	59	51
6	10000	170	228	156	92	69	80	107	73
6	100000	(PMP: 213)		197					93
24	150	94	110	96	102	87	32	38	33
24	200	99	117	101	102	86	34	40	35
24	1000	135	167	140	103	84	47	58	48
24	10000	212	279	192	91	69	73	96	66
24	100000	(PMP: 290)		237					82
192	150	156	163	165	106	101	43	45	45
192	200	163	171	170	105	99	45	47	47
192	1000	205	225	201	98	90	56	62	55
192	10000	285	331	250	88	75	78	91	69
192	100000	(PMP: 363)		299					82

Table 9.7 Rainfall comparisons for Dolydd

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	49	56	51	103	90	43	48	44
1	200	53	61	54	103	89	45	53	47
1	1000	76	98	78	103	80	66	84	67
1	10000	128	192	117	91	61	111	165	100
1	100000	(PMP: 116)		156					135
6	150	96	114	92	96	81	44	52	42
6	200	101	123	97	96	79	46	56	44
6	1000	138	182	126	91	69	63	83	57
6	10000	215	318	169	78	53	98	145	77
6	100000	(PMP: 220)		212					96
24	150	148	187	154	104	82	42	53	43
24	200	154	198	160	104	81	44	56	45
24	1000	196	276	195	100	71	55	78	55
24	10000	276	444	244	89	55	78	126	69
24	100000	(PMP: 353)		292					83
192	150	311	325	334	107	103	59	62	63
192	200	321	340	343	107	101	61	65	65
192	1000	382	432	390	102	90	73	82	74
192	10000	489	611	454	93	74	93	116	86
192	100000	(PMP: 526)		514					98

Table 9.8 Rainfall comparisons for Kew

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	43	57	54	125	94	29	38	36
1	200	46	63	57	125	91	31	42	38
1	1000	66	103	79	119	77	44	68	52
1	10000	111	208	126	113	61	74	139	84
1	100000	(PMP: 150)		186					124
6	150	64	80	72	112	91	30	38	34
6	200	69	86	76	111	89	32	40	36
6	1000	98	131	106	109	81	46	62	50
6	10000	162	239	163	101	68	76	113	77
6	100000	(PMP: 212)		224					106
24	150	83	102	84	101	83	31	38	31
24	200	89	109	89	100	81	33	41	33
24	1000	123	157	119	97	75	46	58	44
24	10000	196	266	176	90	66	73	99	65
24	100000	(PMP: 269)		238					88
192	150	134	134	120	90	90	40	40	36
192	200	140	140	124	88	88	42	42	37
192	1000	181	186	149	82	80	54	56	44
192	10000	260	279	199	76	71	78	84	60
192	100000	(PMP: 334)		261					78

Table 9.9 Rainfall comparisons for St Mawgan

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150	38	49	51	133	104	31	40	41
1	200	41	53	54	133	102	33	43	44
1	1000	59	85	74	126	87	48	69	60
1	10000	99	165	102	103	62	80	134	83
1	100000	(PMP: 123)		130					106
6	150	68	78	77	113	98	34	40	39
6	200	72	84	81	112	96	36	42	41
6	1000	102	124	103	101	84	52	62	52
6	10000	168	215	135	80	63	85	108	68
6	100000	(PMP: 198)		166					84
24	150	97	107	106	109	99	33	37	36
24	200	102	113	110	108	98	35	39	38
24	1000	139	156	136	98	87	48	54	47
24	10000	217	248	171	79	69	75	85	59
24	100000	(PMP: 290)		205					71
192	150	177	159	163	92	103	45	41	42
192	200	184	166	169	92	102	47	42	43
192	1000	228	208	203	89	97	58	53	52
192	10000	308	290	248	80	85	79	74	63
192	100000	(PMP: 392)		290					74

Table 9.10 Rainfall comparisons for Aldergrove

Duration (h)	Return period (y)	FSR rainfall (mm)	FEH DDF rainfall (mm)	New DDF rainfall (mm)	New as % FSR (%)	New as % FEH (%)	As a % of FSR PMP		
							FSR	FEH	New
1	150		39	48		123			
1	200		42	51		122			
1	1000		65	70		108			
1	10000		122	97		80			
1	100000			125					
6	150		60	60		99			
6	200		65	63		98			
6	1000		93	83		90			
6	10000		156	112		72			
6	100000			141					
24	150		90	85		95			
24	200		95	90		94			
24	1000		130	112		86			
24	10000		202	144		71			
24	100000			175					
192	150		133	128		96			
192	200		138	133		96			
192	1000		173	159		92			
192	10000		239	194		81			
192	100000			229					

(No digital FSR maps available for NI)

Table 9.11 Number of locations, out of the 66 GB test sites, where, according to the new model, the return period of FSR PMP exceeds 100,000 years

Duration (hours)	Number of locations	Percentage
1	6	9
2	16	24
6	44	67
24	64	97
192	58	88

9.3 Comparisons at the locations of the 26 extreme events

9.3.1 General assessment

Section 3.7 has summarised, and Appendix B tabulates, the database of 63 extreme observed storm events from the period 1880 to 2006. The following analysis has been applied to a subset of 26 of these events, where the rainfall was at least 70 per cent of FSR PMP, but omitting event 35, Loch Quoich, 1935, for which there is insufficient local raingauge data to reliably estimate the median rainfalls required for the new model. The return period has been estimated for each of the 26 events using the FSR, FEH and the new models (in the latter case using median rainfalls estimated from surrounding gauges) applied to the tabulated rainfall amount and duration. In addition, the event rainfall has been compared with the estimated rainfall for the same duration using the new method for return periods of 35,000 years and 100,000 years. The former return period has been included because it is, in the FSR, the implicit return period of a large part of the envelope line (for England and Wales) of all the known maximum values at that time (*FSR II 4.3.2*). These results are presented in Table 9.12.

The most notable aspect of these results is that 10 out of the 26 events have been assessed by the new DDF model as having a return period in excess of 100,000 years. Most of these are the longer duration events. Out of the nine events that have a duration of 5 hours or longer, eight have an estimated return period of over 100,000 years. The only event of duration 2 hours or less in the 100,000+ year category is the 1989 Halifax storm (Walshaw Dean Reservoir). Figure 9.31 shows how the estimated return periods relate to duration.

This finding about the estimated return periods for the longer durations being high is consistent with the final point in Section 9.2 above (estimated return period of FSR PMP increasing with duration), and two of the previously suggested explanations – systematic errors in the new model that vary with duration, or a variation in the return period of PMP with duration (assuming these extreme events are approaching PMP) – could apply here.

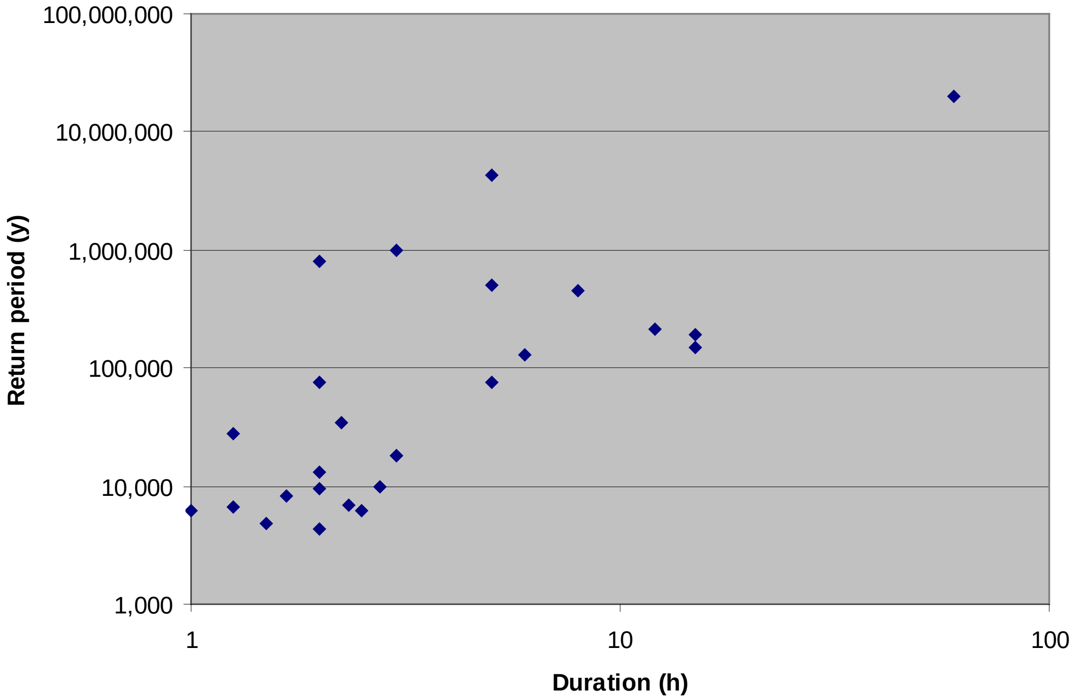

Figure 9.31 Relationship between return period from the new DDF model and duration for the extreme events shown in Table 9.12

Table 9.12(a) Comparison of rainfall statistics for extreme events ≥ 70% FSR PMP (ordered by date)

No.	Year	Location	E	N	SAAR (mm)	Rain (mm)	Dur. (h)	FSR PMP (mm)	Rain as % of FSR PMP	New DDF 35000 year rain (mm)	Rain as % of new DDF 35000 year rain	New DDF 100000 year rain (mm)	Rain as % of new DDF 100000 year rain	Estimated return period (y)		
														FSR	FEH	New DDF
5	1895	Churchstoke	3264	2933	747	123	2	161	76%	140	88%	158	78%	7,000	3,800	13,000
7	1900	Ilkley	4120	4470	978	137	1.25	146	94%	141	97%	158	87%	20,000	3,800	28,000
8	1901	Maidenhead	4886	1814	650	108	1	141	76%	162	66%	198	54%	7,000	570	6,300
10	1908	Portland	3696	742	768	175	5	204	86%	159	110%	181	97%	15,000	3,800	75,000
11	1910	Wheatley	4597	2058	649	139	2	164	85%	202	69%	234	59%	10,000	3,400	4,400
15	1917	Bruton	3684	1350	863	243	8	238	102%	184	132%	208	117%	40,000	11,000	450,000
17	1924	Brymore	3246	1394	758	225	5	218	103%	152	149%	167	134%	35,000	13,000	4,300,000
20b	1930	Castleton	4688	5080	835	304	60	348	87%	211	144%	227	134%	15,000	2,400	20,000,000
23	1932	Cranwell	5000	3499	593	131	2	182	72%	155	84%	174	75%	8,000	1,600	9,400
25	1934	W. Wickham	5382	1654	702	119	1.66	165	72%	161	74%	197	61%	6,000	1,100	8,300
26	1935	Swainswick	3756	1681	840	152	2.75	190	80%	187	81%	216	70%	10,000	4,200	9,800
28	1938	Bovey Tracey	2817	784	1018	149	2.25	167	89%	149	100%	171	87%	8,000	3,600	34,000
29	1941	Newcastle	4240	5640	648	110	2.33	149	74%	139	79%	158	70%	3,500	2,600	6,900
31	1947	Wisley	5060	1597	628	128	1.25	151	85%	181	71%	217	59%	10,000	1,500	6,600
32	1948	Tweed Valley	3710	6347	636	158	15	261	60%	141	112%	153	103%	9,000	4,900	150,000
34	1952	Lynmouth	2708	1428	1815	229	12	328	70%	197	116%	216	106%	6,000	1,900	210,000
36	1955	Martinstown	3648	888	998	280	15	278	101%	235	119%	262	107%	40,000	6,900	190,000
37	1956	Bradford	4072	4355	1080	165	2	168	98%	154	107%	169	98%	20,000	5,100	75,000
38	1957	Camelford	2105	833	1393	203	6	238	85%	182	112%	199	102%	15,000	3,400	130,000
40	1958	Knockholt	5467	1585	820	131	2.5	184	71%	185	71%	221	59%	5,000	920	6,200
41	1960	Horncastle	5251	3695	624	184	3	182	101%	141	131%	154	119%	40,000	3,800	990,000
42	1963	Southery	5612	2932	565	150	3	175	86%	162	92%	183	82%	12,000	2,400	18,000
44	1967	Dunsop Valley	3653	4533	1804	117	1.5	140	84%	153	77%	172	68%	5,000	960	4,800
52	1975	Hampstead	5265	1825	624	171	3	195	88%	193	89%	228	75%	15,000	1,600	18,000
56	1989	Halifax	3967	4336	1379	193	2	162	119%	142	136%	159	121%	40,000	5,800	800,000
62	2004	Boscastle	2130	903	1253	200	5	210	95%	157	128%	174	115%	20,000	4,200	500,000

Table 9.12(b) Comparison of rainfall statistics for extreme events ≥ 70% FSR PMP (ordered by duration)

No.	Year	Location	E	N	SAAR (mm)	Rain (mm)	Dur. (h)	FSR PMP (mm)	Rain as % of FSR PMP	New DDF 35000 year rain (mm)	Rain as % of new DDF 35000 year rain	New DDF 100000 year rain (mm)	Rain as % of new DDF 100000 year rain	Estimated return period (y) FSR	FEH	New DDF
8	1901	Maidenhead	4886	1814	650	108	1	141	76%	162	66%	198	54%	7,000	566	6,300
7	1900	Ilkley	4120	4470	978	137	1.25	146	94%	141	97%	158	87%	20,000	3,785	28,000
31	1947	Wisley	5060	1597	628	128	1.25	151	85%	181	71%	217	59%	10,000	1,462	6,600
44	1967	Dunsop Valley	3653	4533	1804	117	1.5	140	84%	153	77%	172	68%	5,000	962	4,800
25	1934	West Wickham	5382	1654	702	119	1.66	165	72%	161	74%	197	61%	6,000	1,134	8,300
5	1895	Churchstoke	3264	2933	747	123	2	161	76%	140	88%	158	78%	7,000	3,768	13,000
11	1910	Wheatley	4597	2058	649	139	2	164	85%	202	69%	234	59%	10,000	3,361	4,400
23	1932	Cranwell	5000	3499	593	131	2	182	72%	155	84%	174	75%	8,000	1,587	9,400
37	1956	Bradford	4072	4355	1080	165	2	168	98%	154	107%	169	98%	20,000	5,051	75,000
56	1989	Halifax	3967	4336	1379	193	2	162	119%	142	136%	159	121%	40,000	5,798	800,000
28	1938	Bovey Tracey	2817	784	1018	149	2.25	167	89%	149	100%	171	87%	8,000	3,624	34,000
29	1941	Newcastle	4240	5640	648	110	2.33	149	74%	139	79%	158	70%	3,500	2,620	6,900
40	1958	Knockholt	5467	1585	820	131	2.5	184	71%	185	71%	221	59%	5,000	920	6,200
26	1935	Swainswick	3756	1681	840	152	2.75	190	80%	187	81%	216	70%	10,000	4,173	9,800
41	1960	Horncastle	5251	3695	624	184	3	182	101%	141	131%	154	119%	40,000	3,819	990,000
42	1963	Southery	5612	2932	565	150	3	175	86%	162	92%	183	82%	12,000	2,386	18,000
52	1975	Hampstead	5265	1825	624	171	3	195	88%	193	89%	228	75%	15,000	1,624	18,000
10	1908	Portland	3696	742	768	175	5	204	86%	159	110%	181	97%	15,000	3,848	75,000
17	1924	Brymore	3246	1394	758	225	5	218	103%	152	149%	167	134%	35,000	13,322	4,300,000
62	2004	Boscastle	2130	903	1253	200	5	210	95%	157	128%	174	115%	20,000	4,160	500,000
38	1957	Camelford	2105	833	1393	203	6	238	85%	182	112%	199	102%	15,000	3,414	130,000
15	1917	Bruton	3684	1350	863	243	8	238	102%	184	132%	208	117%	40,000	11,077	450,000
34	1952	Lymmouth	2708	1428	1815	229	12	328	70%	197	116%	216	106%	6,000	1,870	210,000
32	1948	Tweed Valley	3710	6347	636	158	15	261	60%	141	112%	153	103%	9,000	4,935	150,000
36	1955	Martinstown	3648	888	998	280	15	278	101%	235	119%	262	107%	40,000	6,919	190,000
20b	1930	Castleton	4688	5080	835	304	60	348	87%	211	144%	227	134%	15,000	2,393	20,000,000

Very few of these events are included in the systematic database of annual maxima that was used to fit the DDF model. Table 9.13 shows the extent to which the events are represented in the daily and hourly raingauge databases used by this study. The words 'mostly' or 'partly' indicate the degree to which the event rainfall was captured by a gauge some distance from the location given in the extreme events table. This tabulation shows that these comparisons have been an almost completely independent check on the new model, but it also indicates the extent to which important data are not currently being incorporated into the model.

Table 9.13 Inclusion of the extreme events in the databases used to fit the DDF model

No.	Year	Location	Rain (mm)	Dur. (h)	Inclusion in hourly database	Inclusion in daily database
8	1901	Maidenhead	108	1	No	No
7	1900	Ilkley	137	1.25	No	No
31	1947	Wisley	128	1.25	No	Mostly (1.8 km away)
44	1967	Dunsop Valley	117	1.5	No	No
25	1934	West Wickham	119	1.66	No	No
5	1895	Churchstoke	123	2	No	No
11	1910	Wheatley	139	2	No	No
23	1932	Cranwell	131	2	No	Yes
37	1956	Bradford	165	2	No	No
56	1989	Halifax	193	2	No	No
28	1938	Bovey Tracey	149	2.25	No	No
29	1941	Newcastle	110	2.33	No	No
40	1958	Knockholt	131	2.5	No	Partly (1.9 km away)
26	1935	Swainswick	152	2.75	No	Partly (1.4 km away)
41	1960	Horncastle	184	3	No	Yes
42	1963	Southery	150	3	No	No
52	1975	Hampstead	171	3	Yes	Yes
10	1908	Portland	175	5	No	No
17	1924	Brymore	225	5	No	No
62	2004	Boscastle	200	5	No	Yes
38	1957	Camelford	203	6	No	No
15	1917	Bruton	243	8	No	No
34	1952	Lymmouth	229	12	No	Mostly (1.8 km away)
32	1948	Tweed Valley	158	15	No	Yes
36	1955	Martinstown	280	15	No	Mostly (3 km away)
20b	1930	Castleton	304	60	No	Partly (6.2 km away)

The spatial and temporal distributions of the 26 selected events are of interest. Including Loch Quoich, the median event in terms of northing is at Wheatley, near Oxford, and 56 per cent of the events occurred during a particular time interval (1930 to 1960), which is only 25 per cent of the overall time period covered by the database (Figure 9.32). If, in future, extreme events were to be used during the model fitting stage, it would be necessary to determine the causes of these uneven distributions and to decide whether or not the selection criteria should be revised.

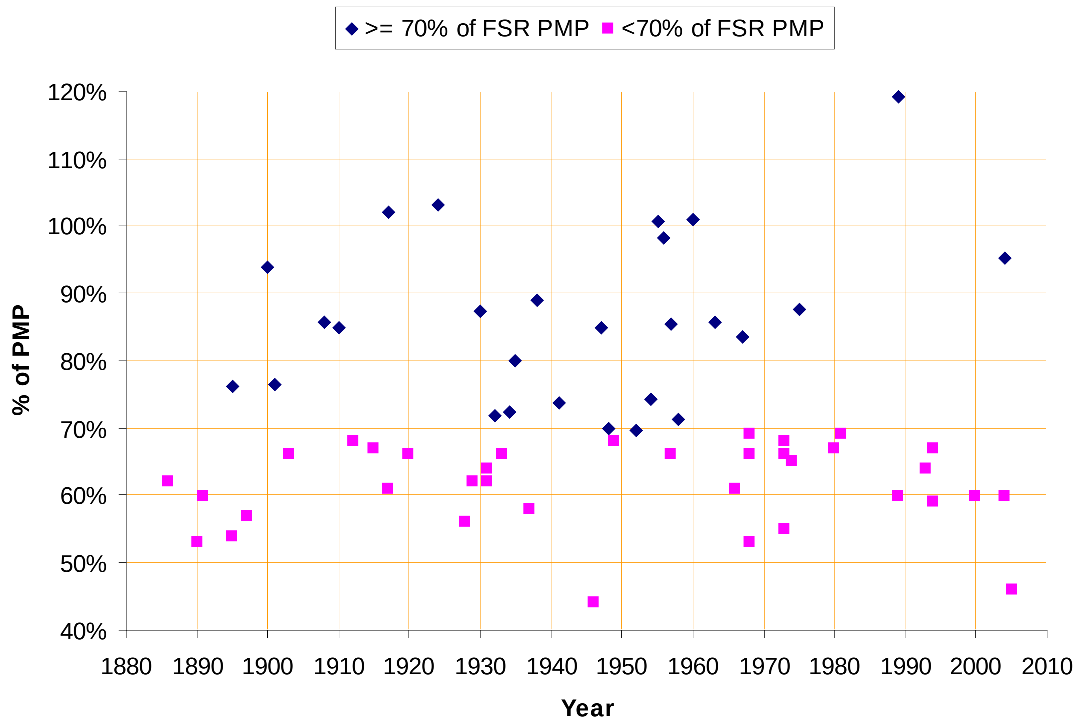

Figure 9.32 Distribution in time of the extreme rainfall events

9.3.2 Statistical assessment

The occurrence of high estimated return periods for events in the extreme event database may be a point of concern and it might be thought that these suggest that the new DDF model is in some way deficient. An objective consideration of this question is made difficult because of the inevitable lack of clarity on several accounts: (i) how any particular event was originally recorded in primary sources, (ii) how they have been selected and are now recorded in the extreme event database, and (iii) whether there have been other events occurring within the same time-period which were not recorded or might have been mislaid.

Of particular concern is that the values in the extreme event database have been collected on an 'event' basis. That is, a single overall 'duration' has been assigned to any one event and the record contains a rainfall total for that duration, but not for any sub-periods. Therefore, an under-recording of time-periods of short duration containing high rainfall totals would be expected simply because those time-periods were part of longer time-periods that were recorded as events of a longer duration. It is known that, in some cases where a description of the event was available with an indication of when the heaviest rain fell, the total event rainfall may have been assigned as occurring within this shorter time interval.

Nonetheless, an analysis of whether or not the return periods of the extreme events are in accord with the DDF model has been attempted which, for clarity, is termed the 'highest return period approach'. If one considers the highest return period assigned to the events of a given duration, a comparison can be sought with the range of values likely to arise as the highest return period from the same configuration of gauges over the same number of years, on the assumption that the true site-wise return periods were known. Therefore, the observed value of the highest return period ascribed to any of the events could be used as a formal test-statistic. The only readily available means of comparison would be based on a model in which this observed highest return period is considered statistically equivalent to the highest return period of annual maxima occurring over a given number of site-years of data, where these site-years are assumed independent, but where some allowance might be made for spatial dependence in determining an appropriate number of site-years to use. An evaluation on this basis is outlined later below.

Alternative threshold counting approach (not used)
An alternative method of statistical assessment that is, perhaps, more immediately linked to the testing of fitted distributions is one based on counting the number of exceedances of some threshold, followed by a comparison of the number found for the count with the distribution of that number according to the model that has been fitted. This will be termed the 'threshold counting approach'. One difficulty with this approach in the present context is that, when combining counts of exceedances across gauges, the statistical distribution of the count is unknown and not easy to approximate using the type of model that has been used here (*i.e.* the spatial dependence model). This is because the spatial dependence model does not fully describe the joint distribution of exceedances of thresholds across several gauges. In a simple version of the assessment, the theoretical mean of the count is easily found, but the corresponding variance is not available. In contrast, the spatial dependence model is much better aligned to the highest return period approach. While the threshold counting approach might be based on rainfall events that happen every 10 or 50 years at individual sites, the highest return period approach is based on the most extreme events experienced across all the gauges collectively and thus may be thought to concentrate on the very extreme events which are of essential interest to the background of this project. The latter approach also allows a good use to be made of the events recorded in the extreme event database, as discussed in Section 9.3.1. This database contains events which are not recorded in the systematic record used for the main part of this project. Therefore, the highest return period approach has been chosen and the rest of the discussion here relates to this approach.

Caveats for the highest return period approach
One difficulty for the sub-daily durations is in determining a relevant number of gauges that might be available to observe extreme events in any particular year. Essentially, no details of the numbers of gauges capable of systematically recording short-duration rainfalls are available for the early years of the data-period, but this might be irrelevant. One interpretation of the events described in *British Rainfall* in the early period is that large rainfalls were recorded at one or more of the daily-read gauges among those reporting as standard, and that

these have been investigated further. In some instances, such daily totals have been ascribed to sub-daily durations on the basis of local reports about how long the event lasted, while in others the keeper of the daily-read gauge was on hand to make sub-daily observations. For the later part of the record there may be more information about sub-daily gauges available, but it seems that an initial identification of potential extreme events would have included examining records from both daily and sub-daily gauges and other sources, and that an event analysis would have combined information from all sources. Although the exact source of the rainfall amounts and the durations ascribed to particular events is often unclear, it may not be unreasonable to work on the basis that the set of locations from which extreme rainfall events might have appeared in the extreme event database is at least as extensive as the set of daily-read gauges.

A second difficulty in dealing with the durations attributed to the events is that the events have been recorded against a single duration only. This means, for example, that it is not possible to determine from the table in Appendix B the 'most extreme rainfall' with a duration of, say, 1 hour because any of the events recorded with a higher duration might have contained a 1-hour total more extreme than those recorded as events with a 1-hour duration.

For the present purposes of assessing the DDF model, 'most extreme rainfall' is determined in the sense of the highest return period rainfall, where return period is evaluated on a site-by-site basis. The tabulation of events in Appendix B was done nominally on the basis that the rainfall amount exceeds a threshold value which varies with duration but is otherwise the same across the whole country. The hope would be that sufficient events would be identified for a given duration that, if return periods were assessed for each event and the maximum of these taken, this would adequately represent the largest return period associated with any total rainfall for the given duration experienced anywhere in the country within the period of record. Note that the 26 events selected from Appendix B and contained in Table 9.12(a) were chosen to be relatively large events when compared with the location-varying value of PMP as determined by the FSR approach. The paucity of events actually tabulated for any one duration indicates that extreme caution is required in assessing the largest return period and it would be best to at least take the largest of the return periods across several neighbouring durations. Table 9.12(b), which is a reformulation of Table 9.12(a), helps with this, as does Figure 9.31.

Range of return periods to be expected

If the above caveats are ignored, or temporarily set aside, the following approach to assessing how large the largest return period should be for a single duration might be taken. As indicated above, the observed outcome (which is the largest return period observed for a given duration) is compared with the statistical distribution associated with observing this largest return period under the assumption that the largest return period is determined as the largest of M individual values each representing the return period of the annual maximum rainfall for a given year at a given site, and under the assumption that these individual values are independent. It is assumed that the value of M has been set so as to take into account any dependence between sites in the same year, so that no further adjustment for dependence is needed within the model. This model can be dealt with in a simple way by converting the return periods into probabilities of non-exceedance: see Appendix L. If an approximation is adopted which is valid when M is large, the theoretical result can be given in the simple form that the probability that the largest return period is less than a value r is α, if

$$r = \frac{M}{-\ln \alpha}.$$

This means, for example, that there is an equal chance of the observed largest return period being greater or smaller than $1.443 \times M$. In terms of a significance test applied to the test statistic defined as the largest return period, the acceptance region for a test at the 10 % significance level is return periods in the interval $0.334 \times M$ to $19.5 \times M$. Similarly, the acceptance region for a test at the 1% significance level is the interval $0.189 \times M$ to $199.5 \times M$. The remaining difficulty is determining an appropriate value for M.

Assessment of the total number of station-years

The quality-controlled systematic record available to this project contains 171,904 station-years of 1-day annual maxima and 17,010 station-years of 1-hour annual maxima. However, account needs to be taken of the total number of known daily-read gauges, not just those digitised and used for the systematic record in this project. Over the twentieth century, the number of daily gauges in the UK varied from just over 3,000 in 1900 to approximately 7,000 in 1975, and down to just over 4,000 in 2000, giving an average of just over 5,000 for any one year. These values are taken from Figure 4.1 of Svensson *et al*. (2009). This gives a total of about 500,000 station-years for the daily gauges in the twentieth century. Account also needs to be taken of the earlier period of record from 1880 onwards, and that after 2000, which would contribute about 35,000 and 16,000 station years respectively. In addition, the contribution of the sub-daily gauges is also required, and this contribution could be larger than the 17,010 station-years of valid annual maxima accepted for this project, but it should be borne in mind that some of the systematic hourly gauges also are included in the systematic daily database. This gives an estimate of the total number of station-years in the region of 568,000, which is comparable to the estimates arrived at in slightly different ways in the two sections below.

Assessment of number of independent station-years (Dales and Reed)

The highest return period approach calls for the number of effectively *independent* station-years rather than the total numbers of station-years. There are no simple arguments for taking account of the spatial dependence. However, it can be noted that spatial dependence would have a greater proportional effect on reducing the effective number of independent sites in years with larger numbers of operational stations than in years with smaller numbers.

If the Dales & Reed model for accounting for spatial dependence is applied in an approximate way, then appropriate conversions of actual gauge numbers to the effective number of independent gauges are listed in Table 9.14. Here, the Dales & Reed model has been applied with the value of AREA set at 233,000 km^2, which is a representative value obtained from the inter-gauge distances using the changing configurations of gauges in the UK over recent years. The values in Table 9.14 relate to a duration of 1 day: the varying dependence for different durations means that number would be increased by a factor of 1.09 for durations of 1 hour and decreased by a factor of 0.95 for a duration of 8 days. The suggestion here is to use a value of 43,000 independent station-years, based on an average of 360 independent sites for 1900-2004 and an average 250 independent sites for 1880 to 1899. The value used might perhaps be increased to 100,000 independent station-years if a computation were to be done for the largest return period across all durations. One may note that these values for the total number of independent station-years effectively ignores the evidence for increased independence at higher return periods found in this project and reported in Section 6 and Appendix E, so that values should be regarded as lower bounds.

Table 9.14 Approximate conversion using the Dales & Reed model to give the effective number of independent gauges in the UK (for daily raingauges: see text)

Actual gauges, N	Effectively independent gauges, N_e
500	157
1000	218
2000	285
3000	327
4000	356
5000	379
6000	397
7000	412
8000	424

Assessment of number of independent station-years (current method)

The spatial dependence model developed in this project has been applied to obtain another estimate of the number of effectively independent station-years. Considerable caution must be applied to the use of the spatial dependence model (specifically, the one which has been fitted within this project) as part of a procedure which is supposed to test the model which has been fitted in this project. However, the results are reported as being the best that are available. An approximate value for the notional number of effectively independent station-years has been derived by making an approximation that the overall set of gauges actually available of the period 1880 to 2004 (whose exact numbers, locations and changes over time are not known) would be broadly equivalent to having a fixed network identical to the configuration supplying valid annual maxima for this project in 1973, which consisted of 4,451 gauges. An indirect calculation using the dependence model developed in this project suggests that this set of 556,375 station-years of record would be equivalent to 252,502 effectively independent station-years. As a check on the earlier discussion, the procedure used here was also applied to the Dales & Reed model and this gave the number of independent station-years as 44,175, which compares well with the earlier 43,000. The radical difference between the numbers derived from the Dales & Reed model and the new model can be explained by noting that the fitting procedure for the Dales & Reed model ensures it gives values appropriate to general values of network maxima, whereas what is needed are values that are appropriate to the extremes of the network maxima.

Results

Based on 250,000 station-years, the acceptance interval for a test at the 10% significance level is 83,500 to 4,900,000 years and there is a probability of ½ that the largest return period lies on either side of 360,000 years. Corresponding values for 500,000 stations-years are obtained by multiplying these values by two. A comparison of the largest estimated return periods in Table 9.12 would cast doubt on both the FSR and FEH methodologies as all of the largest return periods observed fall outside the acceptance region. In contrast, the new DDF model has many more return periods within the above acceptance interval. Depending on which results are discarded because the estimated return period has been exceeded by the return period for a neighbouring duration, only a few results lie below the lower limit and one above. Therefore, the results for the new DDF model are not particularly out of line with the outcome expected according to the assessment scheme outlined here, although the upward trend in the return periods evident in Figure 9.31 is of some concern.

If the assessment were based on the effective number of independent station-years suggested by the Dales & Reed model of, say 44,000 years, the acceptance region at the 10% significance level would be 15,000 to 860,000 years. The return periods calculated from the FEH model for the extreme events are again all lower than the lower bound of what is assessed as reasonable outcomes. If some mixing of results across neighbouring durations is applied in Table 9.12(b), the FSR model results might be interpreted as reporting the largest return periods observed as being from 20,000 to 40,000 years, which would be within the acceptance interval for any one duration. When compared with this lower acceptance region, the largest return periods reported by the new DDF model are now more evenly spread above and below the outer limits than they were for the higher interval.

Of course, the validity of all of these conclusions, particularly those relating to the FSR and FEH results (where we might be thought to be biased) would need to be considered in the light of the doubts cast above over the provenance, and also the relevance to this question, of the extreme value database. In addition, the conclusion is affected by substantial approximations and guesses. Unfortunately, limited resources have prevented a more thorough assessment of the results. It might have been possible to make use of the spatial dependence model fitted within this project as part of the assessment, but even this would still leave a substantial set of guesses and approximations to be made. It can be argued that the extreme event database does not really provide good information about the most extreme return period events experienced in the UK, partly because of the limitations of coverage of the underlying data resources, and partly because it was not designed for this purpose (being targeted at extreme events defined in terms of rainfall event totals).

9.4 Summary

This section has presented two sets of comparisons of the rainfall estimates from the model developed in this project with those from the existing FSR and FEH schemes. At present, the application of the new scheme is limited by the need to determine reliable estimates for the median annual maximum rainfalls across the 11 hourly and daily durations. Such estimates are only readily available at, or very close to, the locations of gauges with reasonably long records (both hourly and daily). In other cases, a manual procedure can be used which takes around an hour for each site.

The first comparison has been carried out for a set of locations which have long records and, in most cases, are close to major reservoirs. Here, an attempt has been made to provide locations spread geographically across the UK. Broad conclusions are that, in comparison with the FEH, for most of the country the new estimates are substantially lower at the 10,000-year return period, and lower or similar at the 150-year return period. Central and northern Scotland shows a different behaviour towards the shorter durations, where the much improved hourly dataset has led to the 150-year estimates being substantially higher than the FEH. Comparison with the FSR is more varied: again, the shortest duration estimates for much of Scotland are higher, and, nationwide, the long duration high return period estimates are generally lower, but there are many other instances where the new and FSR estimates are similar. At the longest applicable duration, 192 hours (8 days), there is generally little difference between the estimates from the three methods at return periods of 100 and 200 years. The sets of results for this first comparison have also allowed a comparison to be made between the estimated frequency curves from the three methods and a simple estimate available from the gauged records for the specific locations. The agreement of the estimates from the new model with the site-based estimates is substantially better than for the older estimates, but this might be expected because the new estimates make full use of the more recent records at the site whereas the older estimates do not. Nevertheless, the comparison here provides a check that there is no disagreement between the locally observed records and the results from the new procedure, which brings in information from a widespread region.

The second comparison has been made using a subset of the extreme events database in which events of variable durations from 1880 to 2006 have been selected as being the most extreme observed across the UK. These events are not necessarily geographically widespread, but they do provide an interesting set of extreme events, being combinations of rainfall amounts and durations that have actually been observed. It is therefore of some interest to evaluate the return periods attributed to these events by the three different estimation procedures. Many of the return periods derived from the new model turn out to be rather high, but a simple statistical argument suggests that they are likely to be of the right order of magnitude.

10. Conclusions and recommendations

10.1 Revised rainfall DDF model for the UK

This project has developed a revised model of rainfall depth-duration-frequency (DDF), which can be applied 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 apply 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 the model published in Volume 2 of the FEH (*Faulkner, 1999*) for hydrological design studies using rainfall-runoff techniques and for assessing the rarity of particular rainfall events in the UK.

10.1.1 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 carried out. Annual maxima were abstracted for eleven key rainfall durations ranging from 1 hour to 8 days. Data were available for over 6,500 daily raingauges (a slight increase in the number used in the FEH), and for 969 hourly gauges, which is twice the number used in the FEH (Section 3). The latter has resulted in short duration rainfall estimates from the new DDF model being substantially higher than those from the FEH in central and northern Scotland. Gauge records were included in the analysis if they were able to provide at least nine annual maximum values. The daily maximum dataset provides very good coverage of the UK. The density of the hourly maximum dataset 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. It should be noted that, while networks of recording raingauges do sometimes exist in such areas, the record lengths are often too short to fulfil the nine-year criterion. This, in turn, implies that it would be worthwhile to update the dataset of hourly maxima 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 to apply to all-year estimates (Section 4.3 and Appendix C). 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*). A list of the events is given in Appendix B. The dataset has been used as a 'reality check' against which the final results of the revised DDF model have been compared.

10.1.2 Revised standardisation

The current project has retained the basic approach to modelling that was taken in the FEH rainfall frequency study, adopting a two-stage index-flood methodology, consisting of a standardisation step followed by the construction of rainfall growth curves through a revised FORGEX procedure. 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 by a revised standardisation expressed by:

$$R_{revised} = 1 + \frac{R - RMED}{f \times RMED} = 1 + \frac{1}{f}\left(R_{standardised} - 1\right) \qquad (10.1)$$

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. Full details are presented in Section 5.

The most marked effects of the revised standardisation arise in cases where the SAAR (standard average annual rainfall) for the target location is different from that of the gauges in the region contributing to the FORGEX procedure. Therefore, for high SAAR locations, there is a tendency to reduce rainfall estimates for a given return period. This is because the standardised rainfalls from nearby sites with low SAAR values are lower than with the original standardisation. Similarly, for low SAAR locations, there is a tendency for estimates to be increased if there are any neighbouring gauge locations with high SAAR values, because standardised rainfall values from these gauges will be higher.

10.1.3 Revised model of spatial dependence

A new model of spatial dependence in rainfall extremes has been developed within this project and has been incorporated into the revised FORGEX procedure to replace the model developed by Dales & Reed (1989). The revised spatial dependence model allows the degree of dependence within a given raingauge network to reduce (that is 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 (*netmax* points) as described in Section 6 and Appendix F. The effect of using the new spatial dependence model within the revised FORGEX procedure is almost always to shift rainfall frequency curves to the right, which increases the return period of a given rainfall depth. Further details are given in Section 7.

10.1.4 Other revisions to FORGEX

This project has made a number of modifications to the FORGEX method described in the FEH. In the revised FORGEX method, rainfall growth curves are fitted to netmax points only, the pooled points being no longer used. In addition, new rules for the definition of network radii have been introduced and additional networks are used up to a radius of 300 km to influence the shape of growth curves at high return period. Finally, new rules have been introduced for the selection of network maxima in the growth curve fitting procedure, and varying weights are attached to the network maxima in this fitting procedure. These revisions produce curves that are a better fit to the data, and which are more spatially consistent.

The combined effect of all of the changes to FORGEX (new standardisation, revised spatial dependence model, and improvements to fitting) is to lower the rainfall frequency curve in almost all cases. This means that there is a general tendency for design rainfall estimates from the revised FORGEX methodology to be lower than those derived from the FEH FORGEX methodology 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. Full details are presented in Section 7.

10.1.5 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. This formulation takes advantage of some basic properties of the Gamma distribution, whereby the shapes of the distributions of totals over different durations can be dealt with in a single family of distributions. The model has a total of 14 parameters and therefore is considerably more complex than that presented in the FEH, which was described by six parameters. The model implies a straight line extrapolation (on the Gumbel scale) of the rainfall frequency curve at very high return periods beyond the range of the data points derived from the revised FORGEX analysis. This is in contrast to the exponential increase of rainfall inherent in the FEH procedure when extrapolated beyond its intended return period limit of 1000 years.

The results of the model fitting stage need to be treated with considerable caution. Estimates of rainfall for the very highest return periods are inevitably based on the occurrence or non-occurrence of very rare events within the period of record. The basis of the overall procedure is to produce estimates that reflect the historical data in a region centred on a target location. However, it has not been possible within the present project to provide a well founded assessment of the uncertainty of the estimated rainfalls. One important aspect of such uncertainty, which has a major effect at extremely large return periods (for example over 10^5 years) is the assumption built into the DDF model that a particular form of extrapolation to high return periods is valid. It is suggested that a standard presentation of results from the model fitting procedure should include the summary values for the extent of rainfall information available from the data from the hourly and daily records from the FORGEX step; examples of these values are shown in Figure 8.6. These values would at least provide an indication of when estimates are being used for return periods which would involve substantial extrapolation beyond the information supplied directly by the historical data.

Currently, the model can be applied at any point of interest whether it is a raingauge site or not, provided that sufficient information is available to estimate a value for the at-site RMED (median annual maximum rainfall) for each of the 11 key durations adopted in this study. It is envisaged that further work in the near future will reapply the method of georegression used in the FEH analysis to map RMED across the UK for each of the required durations (see Section 10.3).

10.2 Summary of results at selected sites

The revised DDF model developed within this project has been fitted to rainfall frequency curves derived from the revised FORGEX methodology at 71 sites across the UK. These sites were chosen on the basis of:

- long hourly and daily raingauge records on the same or adjacent sites;
- inclusion of a high altitude site together with a site at lower altitude in the same area;
- inclusion of sites close to reservoirs and sites improving the coverage of the UK.

The results at each site have been compared with rainfall frequency estimates derived from both the FEH and the FSR. Maps summarising these comparisons are provided in Section 9 and Appendix K. When compared with rainfall estimates from the FSR and FEH methods over durations ranging from 1 hour to 8 days and return periods ranging from 100 to 10,000 years, there are two major differences. Firstly, the estimates from the new model are higher over most of Scotland at the shortest durations. This is mainly due to the improvements to the hourly dataset. Secondly, the estimates from the new model are lower at high return periods. This is due mainly to the improved model of spatial dependence. At extremely large return periods, estimated rainfalls from the new DDF model are lower than those of the FEH model. This is because the former uses an approximately straight line extrapolation, 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.

In addition to these comparisons, Section 9 also considers how these estimates relate to rainfall frequency estimates obtained directly from the raingauges at the 71 selected sites. This comparison shows a good match to the new DDF model, while the other methods perform less well. However, this finding is likely to be explained by the fact that the older methods did not have the advantage of using the more recent data.

Finally, Section 9 reports the estimated return periods of some of the larger events contained in the extreme event database (Appendix B) derived from the new model. While some very large return periods are associated with these events by the new method, it is argued that these results are to be expected, and so do not cast doubt on the new DDF model.

10.3 Model implementation

Currently, results from the revised DDF model are only available for the 71 test sites discussed in this report. A full UK-wide implementation of the model will require estimates of RMED for each of the 11 key durations to be available at every possible point of interest. In the implementation of the FEH rainfall model, the six model parameters were estimated at every point on a 1-km grid of the UK. However, the FEH model had been fitted to a more limited set of eight durations for which maps of RMED were available. During the current analysis, various problems have been identified with the FEH RMED maps for sub-daily durations. In particular, RMED values derived from the new dataset did not correspond well with mapped values. It is thought that the main reason for this is the higher density of hourly raingauges now available. Another reason may be the increase in average record length of the new sub-daily dataset.

It is proposed that a new software package should be developed to replace the FEH rainfall model utility which is currently available on the FEH CD-ROM. This will require the following steps:

- Mapping of RMED for each of the 11 key durations used in this project for the entire UK on a 1-km grid (possibly with higher resolution in high relief areas).
- Development of a set of rainfall frequency curves from the revised FORGEX methodology for the 11 durations at each grid point.
- Fitting of the revised DDF model at each grid point.
- Estimation of DDF model parameters for catchment average rainfalls – possibly by averaging the point values.
- Software developments to handle the revised model and to provide a revised user interface.
- Release of the new version of FEH CD-ROM.

It is likely that this work will form the basis of a follow-on project that is estimated to take about 12-18 months.

10.4 Interim user guidance

It will not be possible to make detailed comparisons between the results of this project and rainfall estimates derived from the FEH or FSR models until the full implementation of the revised DDF model is available. Defra's *Revised Guidance to Panel Engineers* (*Defra, 2004*) states that the FEH should not be used for assessing rainfall of 10,000-year return period and that, for 1,000-year rainfall estimation, assessments should be carried out using both the FEH and FSR methodologies. Maps comparing the results of the current project with the FEH and FSR models for 71 test sites are provided in Appendix K. It is hoped that these will help users to assess the likely effects of adopting the revised DDF model for rainfall risk analysis.

10.5 Recommendations for further research

10.5.1 Reservoir flood risk assessment

This project aimed to develop an improved model of rainfall depth-duration-frequency to replace the FEH model for the return periods relevant to reservoir flood risk assessment (that is return periods from 100 to 10,000 years). However, the final revised DDF model can be applied over the full range of return periods from 2 to over 10,000 years, and it is proposed that it should eventually replace the FEH model entirely. The results of this project indicate that the differences between the revised model and the FEH for return periods of less than 100 years are generally small and result largely from the improved dataset of short-duration maxima.

While this project has re-evaluated methods of rainfall frequency estimation, other related aspects relevant to reservoir flood risk assessment outside the scope of the current analysis need considering further. Some of these are discussed below.

Estimation of PMP

As discussed in Section 1.1, the use of estimates of probable maximum precipitation (PMP) to generate PMF (probable maximum flood) estimates still forms part of the guidance to panel engineers in the assessment of reservoir flood safety (*ICE, 1996*). In the UK, the PMP values come from the FSR analysis published in 1975, even though various studies have recognised that storm rainfalls exceeding PMP have been recorded on a number of occasions.

If PMP is to form part of future guidance to reservoir engineers, there is an obvious need to revisit methods of PMP estimation, to investigate its relationship to rainfall frequency estimates and to consider the effect of climate change. Particular consideration should be given to whether the concept of PMP should be treated as giving a physical upper bound to the amount of rainfall that could occur under any circumstances. An alternative is to treat PMP simply as a rainfall having a particular, formally stated, return period. If values for PMP (of either type) can be created in a systematic way for the whole of the UK, and if this includes a quantitative assessment of uncertainty of such values (which is entirely missing at present), then it might be possible to merge such information into estimates of extreme rainfall obtainable from the type of analysis used in this report. Cox (2003) outlines suggestions as to how this might be achieved.

Rainfall-runoff modelling for reservoir safety
This project has considered one of the design inputs (that is rainfall estimates for high return periods) to the type of hydrological model commonly used for flood risk assessment within reservoir safety studies. However, the study has not investigated the use of rainfall-runoff models, and there is a need for further research on this issue. Volume 4 of the FEH (*Houghton-Carr, 1999*) includes guidance on reservoir flood estimation based on the FSR unit hydrograph and losses model. Although the use of this model has been largely superseded by the Revitalised Flood Hydrograph (ReFH) model (*Kjeldsen, 2007*), the latter has been calibrated to produce design flood events with a return period of up to 150 years.

Recalibration of ReFH
The ReFH model for design hydrograph analysis was calibrated using design rainfall estimates derived from the FEH. It is recommended that a recalibration of the model using the outputs from the revised DDF model should be carried out in due course.

10.5.2 Climate change

The revised DDF model developed within this project, like other aspects of the FEH analysis, is based on the assumption of a stationary climate. The likely effects of climate change on the frequency of extreme rainfall in the UK are not well understood, although Section 4.4 has summarised some of the recent work on this topic. Research on climate change in relation to extreme rainfalls can be divided into two main areas. Firstly, there are analyses of observed records to try to detect trends and, in particular, the direction of any trends. These will, no doubt, be repeated as more data are accumulated, and this approach will rely on maintaining good quality control of such new data. Secondly, there are analyses which attempt to draw conclusions from rainfall data simulated by climate models. Here there are many points which need to be clarified, including whether these models are able to adequately simulate point rainfalls as opposed to rainfalls over rather large regions, as well as the consideration of the actual basis of supposedly random fluctuations within results from these models. Specifically, clarification is needed of the extent to which these results reflect 'real' chaotic behaviour in the climate system as opposed to random error deliberately added so that the fluctuations in the values match those in observed rainfalls. In addition, there are practical questions of whether these computationally expensive models can be used to generate long enough series to adequately estimate very long return period rainfalls.

10.5.3 Future developments of extreme rainfall estimation

Successfully implementing this project's outputs for general rainfall estimation will rely on further research effort, particularly with respect to improving the estimates of the median rainfalls which are currently available. In the longer term, improvements in estimating extreme rainfall will depend on developments in a number of research areas, some of which are outlined below. Many of these topics are interlinked.

Analysis of very short duration rainfalls

Many of the agencies which provided data used for this project actually hold rainfall data at a 15-minute resolution. It may, therefore, be possible to obtain a spatially widespread dataset of reasonable record length to which the present methodology might be applied. However, it is expected that there would be many large gaps in the spatial distribution of such data, since the coverage would be poorer than for the 1-hour data used here. Fifteen-minute resolution would be an improvement on the 1-hour resolution for some important applications such as drainage design, although even finer resolution is actually needed. Some data-holders do hold data on a time-of-tip basis, notionally at a 1-second resolution. The spatial extent of such records is not likely to provide a complete coverage of the UK, but they may provide a basis for some exploratory data analysis. Very fine resolution data are required for topics such as the effect of extreme rainfalls on the intermittent blockage of microwave signals.

Improved characterisation of orographic effects

For logistical reasons, the sets of orographic descriptors used for parts of the FEH analyses were unavailable to this project, but they should be available from now on. Future work should consider the possibility of increasing these, as the early exploratory analyses in this project highlighted orography and location as important explanatory factors for the different behaviours of rainfall extremes.

Improved RMED mapping

The availability of good estimates of median rainfalls for all locations in the UK, and for all standard durations, is a key to the methodology proposed within this project. The topic is interlinked with many others, as improved estimates may depend on improved orographic descriptors, and estimates of median rainfall may be required for seasonal as well as annual maximum rainfalls, depending on the overall approach taken within any newly developed statistical methodology. An improved methodology might allow account to be taken of the difference between sites of the years of recorded data and how these relate to any short-term climate variations. There is a need to ensure that estimates of median rainfalls progress smoothly as the duration considered changes. Estimates of extreme rainfalls are strongly dependent on the estimated medians and, for this reason, it is important to be able to provide good estimates of median rainfall for locations which are either isolated geographically or atypical of the majority of existing gauged locations, such as those at high altitudes.

Seasonal analyses

At present there is some demand for estimates of extreme rainfall on a seasonal basis, but mainly for more moderate return periods than those required for reservoir design. The present methodology could potentially be applied to separate analyses for different seasons. The missing component here is the required estimates of median maximum rainfalls for the different seasons. However, the implications of being able to carry out separate seasonal analyses are not limited to those immediate outputs. It may well be that substantially improved estimates of rainfall extremes on an annual maximum basis can be obtained by combining separate analyses of different seasons.

Diurnal analyses
There have been studies which show that the frequency of occurrence of extreme rainfalls of short duration varies within the day, at least in some regions of the UK. While, in principle, this topic is similar to that of seasonal analyses, the need to have estimates of extreme rainfall associated with particular times of day may arise in different types of application such as drainage design.

Updating the database of maxima
An important contribution to improving rainfall estimates can be made in some areas of the UK by data records accumulated since the data were obtained for this project. There are known to be existing raingauges with records that were too short to be used for the present project that could now contribute, if their records are of reasonable quality. In particular, these would contribute greatly to the improved spatial estimation of median rainfalls in upland areas. Of course, any future work would benefit from the general extension of existing record lengths, but experience has shown that substantial effort is required to maintain a consistently good level of quality control. In addition, it is known that a very substantial number of pre-1961 daily raingauge accumulations and a number of hourly raingauge accumulations exist in manuscript and chart form, and the digitisation of such records would be of great value to future studies of rainfall frequency.

At present there is no single mechanism for archiving and providing public access to rainfall records. Similarly, where records of extreme rainfalls have been abstracted for particular purposes, there are no ongoing ways of updating and maintaining these records.

Use of extreme event data
The archive of extreme rainfall events which has been constructed during this project has been used in comparisons with design rainfall estimates derived from the revised DDF model. Further research might be able to use the event information as netmax values to increase those available from the systematic record. Information about the development of raingauge networks through time across the UK has already been compiled (a prerequisite for inclusion of the non-systematic data), but time did not allow this approach to be investigated during the current project.

Effect of raingauge instrumentation
In the UK, hourly and sub-hourly rainfalls have been recorded using a number of different technologies, which may have different effects on the estimation of extreme rainfalls. Information about raingauge instrumentation has not been available on a consistent basis for the records used by this project, but there may be some potential for making use of such information.

Cross-duration relationships
Part of the analysis carried out in this project involves using simple multiplying factors to make use of the observed maxima for fixed and semi-sliding durations as if they had been fully-sliding maxima. There is scope to reassess this step, both in terms of empirical data analyses, extended beyond those carried out for this project, and in terms of theoretical considerations of how the maxima of

different types should relate. This project's methodology treats analyses of the different durations separately at several stages of the procedure, and there may be scope for improving the procedure by imposing more consistency across durations at these stages.

Improvements to the present statistical approach

If a statistical methodology of the same overall structure as the one used in this project were to be retained in future analyses, the results may well improve from re-evaluating either of the important sub-stages of standardisation and spatial dependence modelling. These improvements might come from improved orographic descriptors, carrying out separate seasonal analyses or from extended datasets.

Alternative statistical approaches

The data analyses and results of this project might be regarded as a useful exploratory analysis for some entirely new approach to analysing either the existing or an extended dataset. Work here has highlighted the importance of treating the annual maximum data for different durations and different locations within the same overall analysis. The structure of the depth-duration-frequency model developed here might provide a guide to suitable assumptions about the form of marginal distributions as the duration varies. The present approach to standardisation, as what is effectively a pre-processing stage, need not be retained, and it may be reasonable to deploy different standardisation relationships based on location in each component, if the two-component formulation of the DDF model is retained.

11. References

Alexander, G. N., 1963. Using the probability of storm transposition for estimating the frequency of rare floods. J. Hydrol. **1**, 46-57.

Alkasasbeh, M. R. & Raqab, M. Z., 2009. Estimation of the generalized logistic distribution parameters: comparative study. Statistical Methodology, **6**, 262-279.

Austin, B. N., Cluckie, I. D., Collier, C. G. & Hardaker, P. J., 1995. Radar-based estimation of Probable Maximum Precipitation and Flood. Report to Water Directorate, Dept. of Environment. Met Office, UK, January 1995, 123 pp.

Bailey, M. J., Carpenter, K. M., Lowther L. R. & Passant, C.W., 1981. A mesoscale forecast for 14 August 1975 – the Hampstead storm. Meteorol. Mag., **110**, 147-161.

Boos, D. D., 1982. Minimum Anderson-Darling Estimation. Communications in Statistics, Part A – Theory and Methods, **11** (24), 2747-2774.

BRE, 1994. Register of British Dams. Building Research Establishment, Watford. 55 pp.

Browning, K. A. & Hill, F. F., 1984. Structure and evolution of a Mesoscale Convective System near the British Isles. Quart. J. R. Met. Soc., **110**, 897–913.

Bullock, A., 1987. Development of the Flood Studies Report regional flood estimation procedure in central Zimbabwe. Proc. British Hydrological Society National Hydrology Symposium, University of Hull, Hull, UK, 14-16 September 1987, pp. 7.1-7.7.

Bureau of Meteorology, 2003. The estimation of probable maximum precipitation in Australia: Generalised short-duration method. Hydromet. Advisory Service, Commonwealth Bureau of Meteorology, Australia, June 2003, 34 pp.

Centre for Ecology & Hydrology, 2009. FEH CD-ROM 3. Centre for Ecology & Hydrology, Wallingford, UK.

Chapman, C. R. & Morrison, D.,1994. Impact on the Earth by asteroids and comets: assuming the hazard, Nature, **367**, 6 January, 33-40.

Chegodayev, N. N., 1953. Computation of runoff on small catchments. Transzhedorizdat, Moscow.

Chow, V. T., 1951. A general formula for hydrologic frequency analysis. Trans. Am. Geophy. Union, **32**, 231-237.

Clark, C. & Pike, W. S., 2007. The Bruton storm and flood after 90 years, Weather, **62**, 300-305.

Collier, C. G., Fox, N. I. & Hand, W. H., 2002. Extreme rainfall and flood event recognition. R&D Technical Report FD2201, Defra/Environment Agency, UK, 58 pp.

Collier, C. G. & Hardaker, P. J., 1996. Estimating probable maximum precipitation using a storm model approach. J. Hydrol., **183**, 277-306.

Collier, C. G. & Lilley, R. B. E., 1994. Forecasting thunderstorm initiation in North-west Europe using thermodynamic indices, satellite and radar data, Meteor. Apps., **1**, 75-84.

Collinge, V. K., Thielen, J. & McIlveen, J. F. R., 1992. Extreme rainfall at Hewenden reservoir, 11 June 1956. Met. Mag., **121**, 166-171.

Cooper, G. A., 1987. The reservoir safety programme in Northern Ireland. J. Instn Wat. Envir. Mgmt, **1**, 39-51.

Cox, D. R., 2003. Some comments on 10,000 year return period rainfall. Report to Defra, 24 pp.

Dales, M. Y. & Reed, D. W., 1989. Regional flood and storm hazard assessment. IH Report No. 102. Institute of Hydrology, Wallingford.

Daniels, H. E. 1982. A Transformation for Normal Extremes. In: Essays in Statistical Science (Eds: Gani J., Hannan E.J.). J. Applied Probability, Special Volume 19A, 201-206

Defra, 2004. Floods and Reservoir Safety (FEH/FSR) - Revised Guidance for Panel Engineers, June 2004. Presently on request from the Defra website http://www.defra.gov.uk/environment/flooding/reservoir/safety.htm

Delicado, P. & N. Goriab M. N., 2008. A small sample comparison of maximum likelihood, moments and L-moments methods for the asymmetric exponential power distribution. Computational Statistics & Data Analysis, **52**, 1661-1673.

Dempsey, P. & Dent, J., 2009, Report on the Extreme Rainfall Event Database. Report No. 8 to Defra, Contract WS 194/2/39, Revised February 2009, 87 pp.

Dent, J., 2008. Uncertainties associated with the estimation of Probable Maximum Precipitation, PMP. Report No. 12 to Defra, Contract WS194/2/39, March 2008, 24 pp.

Dwyer, I. J. & Reed, D. W., 1995. Allowance for discretization in hydrological and environmental risk estimation (ADHERE). IH report No. 123. Institute of Hydrology, Wallingford, UK.

Eden, P., 2009, From Observations to Forecasts – Part 1. Traditional weather observing in the UK: An historical overview. Weather, **64**(9), 239-245.

Ekström, M., Fowler, H. J., Kilsby, C. G. & Jones, P. D., 2005. New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies. J. Hydrol., **300**, 234-251.

Fankhouser, R., 1998. Influence of systematic errors from tipping bucket rain gauges on recorded rainfall data. Wat. Sci. Tech., **37**, 121-129.

Faulkner, D., 1999. Rainfall frequency estimation. Volume 2 of the Flood Estimation Handbook, Institute of Hydrology, Wallingford.

Faulkner, D. S. & Prudhomme, C., 1998. Mapping an index of extreme rainfall across the UK. *Hydrol. & Earth System Sci.*, **2**, 183-194.

Fitzgerald. D. L., 2007. Estimation of Point Rainfall Frequencies. Met Éireann Technical Note 61. Met Éireann, Dublin, Ireland, 47 pp.

Fountaine, T. A. & Potter, K. W., 1989. Estimating probabilities of extreme rainfalls, J. Hydraulic. Eng., **115**, 1562-1572.

Fowler, H. J., Ekström, M., Kilsby, C. G. & Jones, P. D., 2005. New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 1. Assessment of control climate. J. Hydrol., **300**, 212-233.

Gray, M. E. B. & Marshall, C., 1998. Mesoscale convective systems over the UK, 1981-97. Weather, **53**, 388-396.

Hand, H. A. & Nagaraja, H. N., 2003. Order Statistics, 3rd Edition. Wiley.

Hand, W. H., Fox, N. I. & Collier, C. G., 2004. A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting. Meteorol. Appl., **11**, 15-31.

Hardaker, P.J., 1996. Estimating probable maximum precipitation for a catchment in Greece using a storm model approach, Meteorol. Appl., **3**, 137-145.

Hershfield, D. M., 1961. Estimating the probable maximum precipitation. Proc. Am. Soc. Civ. Eng. Hydraulics Div., **87**, 99-106.

Hershfield, D. M., 1965. Method of estimating probable maximum precipitation, J. Am. W. W. Assn., **57**, 965-972.

Hodgkinson, R. A., Pepper, T. J. & Wilson, D. W., 2004. Evaluation of tipping bucket rain gauge performance and data quality. Report to the Environment Agency, Science Report W6-048/SR. Environment Agency, Bristol, UK.

Hosking, J. R. M., 1990. L-moments: Analysis and Estimation of Distributions using Linear Combinations of Order Statistics. Journal of the Royal Statistical Society, Series B, **52,** 105-124.

Hosking, J. R. M.,1992. Moments or L moments? An example comparing two measures of distributional shape. The American Statistician, **46**,186-189.

Hosking, J. R. M., 2006. On the characterization of distributions by their L-moments. Journal of Statistical Planning and Inference, **136**, 193-198.

Hosking, J. R. M. & Wallis, J. R., 1997. Regional Frequency Analysis: An Approach Based on L-moments. Cambridge University Press.

Houghton-Carr, H., 1999. Restatement and application of the Flood Studies Report rainfall-runoff method. Volume 4 of the Flood Estimation Handbook, Institute of Hydrology, Wallingford.

Houze, R. A., 1993. Cloud dynamics. Int. Geophys. Ser., **53**, pp. 334-404.

Hughes, C., Strangeways, I. C. & Roberts, A. M., 1993. Field evaluation of two aerodynamic raingauges. Weather, **48**, 66-71.

ICE, 1996. Floods and reservoir safety, 3rd ed.. Publ. by Thomas Telford for the Institution of Civil Engineers, London. 63 pp.

Institute of Hydrology, 1999. Flood Estimation Handbook (five volumes). Institute of Hydrology, Wallingford.

Jones, D. A., 1997. Plotting positions via maximum-likelihood for a non-standard situation. Hydrol. and Earth System Sci., **1**, 357-366.

Jones, M. C., 2004. On some expressions for variance, covariance, skewness and L-moments. Journal of Statistical Planning and Inference, **126**, 97-106.

Jones, M. C., 2009. Kumaraswamy's distribution: A beta-type distribution with some tractability advantages. Statistical Methodology, **6** (1), 70-81.

Journel, A. G., Huijbregts, C. J., 1978. Mining geostatistics. Academic Press, London, UK.

Kjeldsen, T. R., 2007. The revitalised FSR/FEH rainfall-runoff method. FEH Supplementary Report No. 1, Centre for Ecology & Hydrology, Wallingford.

Kjeldsen, T. R., Prudhomme, C., Svensson, C. & Stewart, E. J., 2006. A shortcut to seasonal design rainfall estimates in the UK. *Water & Environment J., CIWEM.*, **20 (**4), 282–286.

Kjeldsen, T. R., Stewart, E. J., Packman, J. C., Folwell, S. S. & Bayliss, A. C., 2005. Revitalisation of the FSR/FEH rainfall-runoff method. R&D Technical Report FD1913/TR, Defra/Environment Agency, 133 pp.

Leadbetter, M. R., Lindgren G. & Rootzen, H., 1983. Extremes and related properties of random sequences and processes. Springer-Verlag.

Lowing, M. J. & Law, F. M., 1995. Reconciling flood frequency curves with the Probable Maximum Flood. Proc. of the BHS 5th National Hydrology Symposium, Heriot-Watt University, Edinburgh, 4-7 September 1995.

MacDonald, D. E. & Scott, C. W., 2001. FEH vs FSR rainfall estimates: an explanation for the discrepancies identified for very rare events. *Dams & Reservoirs*, **11**, 2., 28-31.

Maraun, D., Osborn, T. J. & Gillett, N. P., 2008. United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006. Int. J. Climatol., **28**, 833-842.

Meigh, J. R., Farquharson & F. A. K., Sutcliffe, J. V., 1997. A worldwide comparison of regional flood estimation methods and climate. Hydrol. Sci. J., **42**, 225-244.

Met Office, 1982. Observer's handbook. Her Majesty's Stationery Office, London, UK.

Muller, A. , Barco J.-N. & Lang, M., 2008. Bayesian comparison of different rainfall depth-duration-frequency relationships. Stoch. Environ. Res. Risk. Assess., **22**, 33-46.

NERC, 1975. Flood Studies Report, five volumes. Natural Environment Research Council, London.

Newton, D. W., 1980. Improving Probable Maximum Flood estimates, Proc. Symp. Surface-Water Impoundments, Univ. Minnesota, ASCE, Am. Water Resour., Am. Geophy. Union, Vol. 1, June, 273-290.

Niemczynowicz, J. 1986. The dynamic calibration of tipping-bucket raingauges. Nord. Hydrol., **17**, 203-214.

Nystuen, J. A., 1999. Relative performance of automatic rain gauges under different rainfall conditions. J. Atmos. Ocean. Technol., **16**, 1025-1043.

Osborn, T. J., Hulme, M., Jones, P. D. & Basnett, T. A., 2000. Observed trends in the daily intensity of United Kingdom precipitation. Int. J. Climatol., **20**, 347-364.

Parr W. C. & Schucany W. R., 1980. Minimum distance and robust estimation. Journal of the American Statistical Association, **75**, 616-624.

Pearson, E. S. & Hartley, H. O., 1972. Biometrika Tables for Statisticians, Volume II. Cambridge University Press.

Reed, D. W. & Field, E. K., 1992. Reservoir flood estimation: another look. IH Report No. 114. Institute of Hydrology, Wallingford.

Reed, D. W., Faulkner, D. S. & Stewart, E. J., 1999. The FORGEX method of rainfall growth estimation – II: Description. Hydrol. and Earth System Sci., **3**, 197-203.

Reed, D. W. & Stewart, E. J., 1989. Focus on rainfall growth estimation. Proc. 2nd National Hydrol. Symp., Sheffield, UK, September 1989, British Hydrological Society, pp. 3.57-3.65.

Reed, D. W. & Stewart, E. J., 1994. Inter-site and inter-duration dependence in rainfall extremes. In Barnett, V. & Turkman, K. F., eds.. Statistics for the environment 2: Water related issues, John Wiley & Sons, 125-143.

Robson, A. & Reed, D., 1999. Statistical procedures for flood frequency estimation. Volume 3 of the Flood Estimation Handbook, Institute of Hydrology, Wallingford.

Royston, P., 1992. Which measures of skewness and kurtosis are best? Statistics in Medicine, **11**, 333-343.

Serfling, R. & Xiao, P., 2007. A contribution to multivariate L-moments: L-comoment matrices. Journal of Multivariate Analysis, **98**, 1765–1781.

Shaw, E. M., 1988. Hydrology in Practice. Van Nostrand Reinhold (International), London.

Skaugen, T. 1997. Classification of rainfall into small- and large-scale events by statistical pattern recognition*. J. Hydrol*., **200** (1-4), 40-57.

Stedinger, J. R., Vogel, R. M. & Foufoula-Giorgiou, E., 1993. Frequency analysis of extreme events. In: D. R. Maidment (ed.), Handbook of Hydrology, McGraw-Hill.

Sutcliffe, J. V., 1980. Use of the Flood Studies Report overseas. Proc. ICE conf. Flood Studies Report five years on, Manchester, UK, July 1980, pp 7-10.

Svensson, C., Jones, D. A., Dent, J. E., Collier, C. G., Stewart, E. J., Anderson, C. W. & Dempsey, P., 2006. Review of rainfall frequency and Probable Maximum Precipitation methods. Report No. 2 to Defra, Contract WS 194/2/39, October 2006, 82 pp.

Svensson, C., Folwell, S., Dempsey, P., Dent, J. & Fung, C. F., 2009. Report on data consolidation, and appendices. Report No. 4 to Defra, Contract WS 194/2/39, Revised April 2009, 74pp.

Tedd, P., Holton, I. R. & Charles, J. A., 1992. The BRE dams database. In Parr, N. M., Charles, J. A. & Walker, S. (eds.). Water resources and reservoir engineering. Proc. Seventh conf. British Dam Society, Stirling, 24-27 June 1992. Tomas Telford, London, pp. 403-410.

Ulrych, T. J., Velis, D. R., Woodbury, A. D. & Sacchi, M. D., 2000. L-moments and C-moments. Stochastic Environmental Research and Risk Assessment, **14**, 50-68.

US Committee on Techniques for Estimating Probabilities of Extreme Floods, 1988. Estimating probabilities of extreme floods, National Research Council, National Academy Press, Washington DC.

Webb, J. D. C. & Pike, W. S., 2007. Thunderstorm squall associated with a mesoscale convective system, 22 July 2006, Weather, **62,** 270-275.

Wiesner, C. J., 1970. Hydrometeorology. Chapman and Hall, 232 pp.

WMO, 1986. Manual for estimation of Probable Maximum Precipitation. Operational Hydrology Report No. 1, World Meteorological Organization, Geneva, Switzerland, 269 pp.

Young, M. V., 2007. Severe thunderstorms over southern England on 10 May 2006, Weather, **62**, 116-120.

Zaidman, M. & Lamb, R., 2005. Review of tipping bucket raingauge performance. Final report to the Environment Agency, order 30032404. JBA Consulting, Skipton, UK, May 2005.