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A new FEH rainfall depth-duration-frequency model for hydrological applications

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Abstract Recent research funded by the Joint Environment Agency/Defra Flood and Coastal Risk Management R&D Programme has developed a new statistical model of point rainfall depth-duration-frequency (DDF) for the UK. The analysis made use of an extensive set of annual maximum rainfall depths for daily and recording raingauges across the UK. The new model will eventually replace the *Flood Estimation Handbook* (FEH) rainfall DDF model to provide estimates of rainfall depth for storm durations ranging from under 1 h to 8 days and return periods from 2 years to >10 000 years. The paper reports on current progress to generalise the new model so that it can be applied at any point, catchment or user-defined area, and potential links between the new model and hydrological applications of weather radar are highlighted.

Key words rainfall; depth-duration-frequency; Flood Estimation Handbook; radar rainfall; urban drainage

INTRODUCTION

Recent research funded by the Joint Environment Agency/Defra Flood and Coastal Risk Management R&D Programme has developed a new statistical model of point rainfall depth-duration-frequency (DDF) for the UK (Stewart *et al.*, 2010a). The model was developed for rainfall durations from 1 hour to 8 days. Although it was originally envisaged that it would be applicable primarily to the long return periods which are typically used in hydrological analyses for reservoir flood risk assessment, the new model has been developed to provide estimates of rainfall frequency for a wide range of return periods from 2 to >10 000 years. Therefore, it is proposed that the new DDF model should eventually replace that published in Volume 2 of the *Flood Estimation Handbook* (FEH) (Faulkner, 1999).

This paper describes the main results obtained from applying the new FEH DDF model at over 70 sites throughout the UK, and discusses recent progress in generalising the model to provide both gridded point and catchment average rainfall frequency estimates. Although work is ongoing to develop a new rainfall model utility which will be delivered within the next version of the FEH CD-ROM (CEH, 2009), other ways of providing access to the new rainfall frequency estimates are currently being explored, which include replacing the use of the existing FEH model within the Hyrad system (Moore *et al.*, 2005).

APPLICATIONS OF THE EXISTING FEH DDF MODEL

Rainfall frequency estimates from the existing FEH DDF model are used in various approaches to hydrological design studies using rainfall–runoff techniques, for example in application of the ReFH design methodology (Kjeldsen, 2007), and for assessing the rarity of particular rainfall events in the UK, and it is the latter application that is most relevant to the hydrological use of weather radar. Until recently, most notable rainfall events have been measured by individual raingauges or gauge networks, but increasingly weather radar is capturing information about the spatial and temporal characteristics of extreme storms, for example the Boscastle event of 2004 (Fenn *et al.*, 2005). The rarity of individual radar-derived catchment average rainfall estimates can be assessed directly using the stand-alone implementation of the FEH DDF model on the FEH CD-ROM 3 (CEH, 2009), but the software does not allow estimates to be derived off-line or for user-defined areas rather than river catchments. Cole *et al.* (2011) describe a recent development of the Hyrad Weather Radar System (Moore *et al.*, 2005) that utilises the existing FEH DDF model to allow post-event analysis of storm events captured by weather radar for Scottish Water. Following flood events, the estimates are used to monitor whether urban drainage systems performed within design specifications or if remedial action is required to comply with the regulatory framework.

DEVELOPMENT OF THE NEW DDF MODEL

Motivation

The FEH (Institute of Hydrology, 1999) introduced a new set of procedures for the estimation of rainfall and flood frequency in the UK. For rainfall frequency, it superseded the previous UK design standard of the Flood Studies Report (FSR) (NERC, 1975). Both methods derive the rainfall frequency curve by multiplying a (local) index variable by a regionally derived growth curve. However, while the FSR used just two regions for the UK, the FEH pools data from circular regions centred on the point of interest, resulting in growth curves that vary relatively smoothly in space. A further innovation of the FEH was to employ annual values of the largest rainfall observed within a region, together with a spatial dependence model, to estimate the regional growth curve at higher return periods than would be available from single gauge records.

The FEH procedures and subsequent updates and refinements have been widely adopted for flood risk management. However, the FEH rainfall DDF model was developed for return periods of up to 2000 years and, especially amongst reservoir engineers, concern has been voiced about the results it produces for the very long return periods used in reservoir flood safety assessment. Babtie Group (2000) compared the FEH DDF model with the FSR, and found that the FEH often gave significantly higher rainfall depth estimates at the highest return periods. MacDonald & Scott (2001) found that in some cases the FEH 10 000-year return period rainfall exceeded the estimate of probable maximum precipitation (PMP) derived from the FSR. On the basis of these concerns, the project was commissioned to consider some aspects of the FEH DDF model at return periods above 100 years, although the final analysis has considered the entire range of return periods from 2 years upwards.

Key components of the new model

The new DDF model was developed using an extensive dataset of annual maximum rainfall depths from raingauges throughout the UK. The possibility of making use of archives of radar data was explored in the early stages of the project, but the task of reconciling raingauge and radar estimates was considered to be too complex to be practicable. However, radar data were utilised in the examination of selected extreme events that were used to validate the final results of the DDF analysis (Dempsey & Dent, 2009).

The development of the new model was based on an extensive statistical analysis of the annual maximum dataset. The basic approach taken mirrored that of the FEH rainfall analysis, but with key revisions: (i) the standardisation of the rainfall maxima is now more complex, making the rainfalls at the different sites more similar prior to data pooling; (ii) the model of spatial dependence now allows the dependence to decrease with increasing return period, rather than being the same for both large and small events; and (iii) changes were made to the pooling methodology to overcome anomalous behaviour observed across a wide range of test cases. In addition, the new model makes use of an extended dataset.

Rainfall frequency curves were produced by the revised methodology for durations from 1 hour to 8 days at 71 test sites and a new DDF model was then fitted to the results. Full details of the analysis are given by Stewart *et al.* (2010a).

Model results

Rainfall frequency estimates from the new DDF model were compared with those derived from the published FEH model at 71 sites throughout the UK. The test sites were selected primarily on the basis of raingauge record length and/or proximity to large reservoirs, and also to give good coverage of the UK. Estimates were derived for 11 key durations from 1 to 192 hours (i.e. 8 days) and for return periods from 100 to 10 000 years. To illustrate the results, Fig. 1(a) shows a map comparing estimates from the new model with the FEH model for a 2-h duration and a return period of 100 years. It can be seen that the estimates from the new model are generally similar to or slightly lower than those from the FEH for most of England, Wales and Northern Ireland. However, in northwest England, at one site in Northern Ireland and for much of Scotland, the new rainfall estimates exceed those from the FEH. This is mainly due to the new, larger dataset available, which comes from a denser network.

From the comparisons for all durations and return periods studied, several notable features emerge. Firstly, the estimates from the new model are higher over most of Scotland at the shortest durations (<6 h). Secondly, the estimates from the new model tend to be lower than the FEH at higher return periods (>200 years) and this is thought to be due mainly to the improved model of spatial dependence (see Fig. 1(b) for an example). At extremely high return periods, estimated rainfalls from the new DDF model are often considerably lower than the FEH model because the extrapolation of the new model is an approximate straight line on the Gumbel scale whereas the FEH model curves upwards (an exponential extrapolation). Finally, whilst FEH 10 000-year rainfall estimates commonly exceeded FSR PMP, this is rarely the case with estimates from the new model.

Areal rainfall frequency

The results discussed thus far were derived by applying the new DDF model at individual sites. These can be used to estimate the rarity of particular rainfall events, usually measured at a single

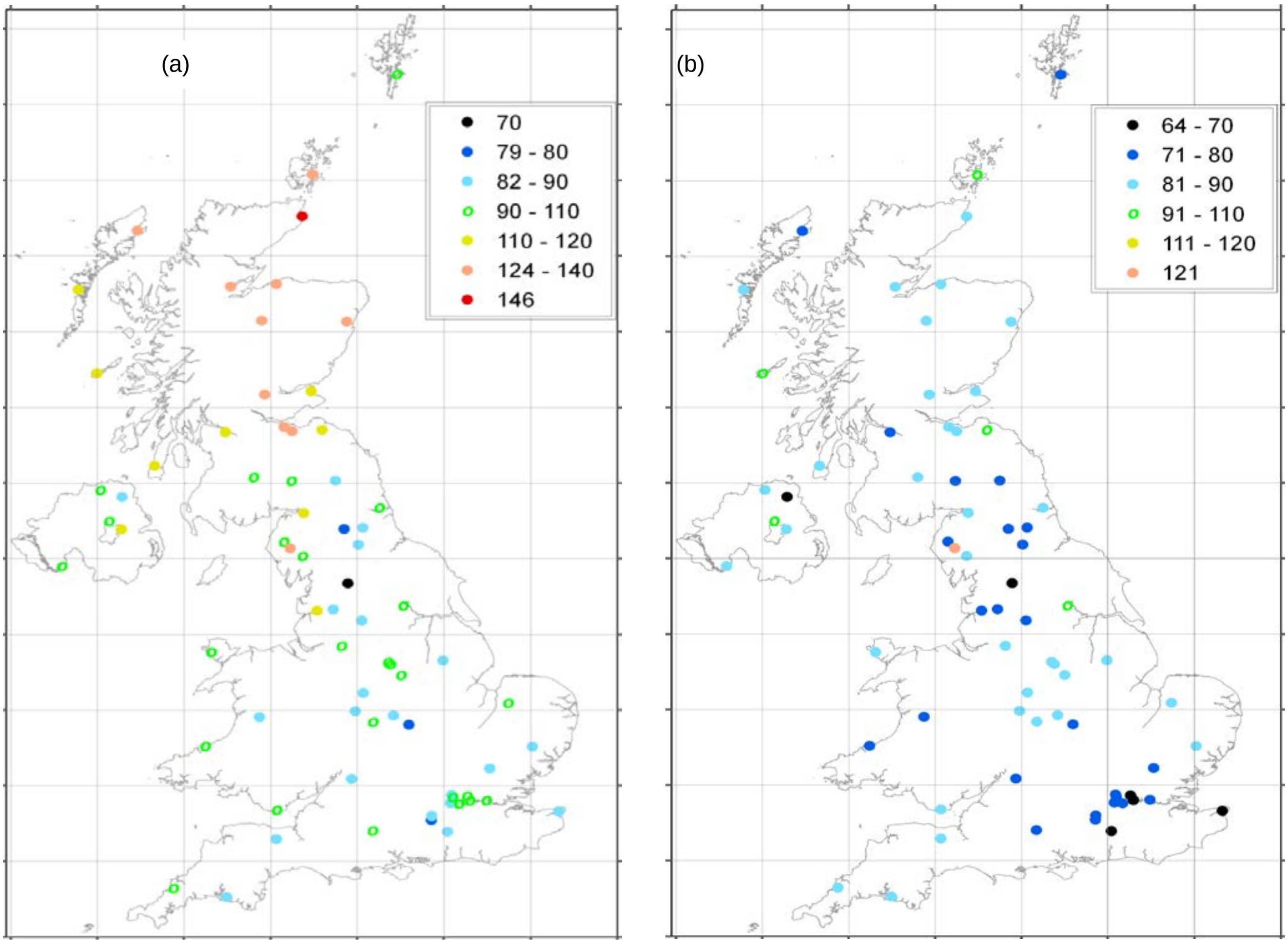

Fig. 1 New rainfall estimates as a percentage of estimates from the FEH model: (a) duration 2 h and return period 100 years, (b) duration 24 h and return period 1000 years.

raingauge. However, many applications require estimates of areal average rainfall frequency over river catchments or storm sewer networks as inputs to hydrological models, or for an ungauged site, and for this reason work is now under way to estimate the parameters of the new DDF model on a gridded basis throughout the UK. As was the case with the FEH model, construction of the new DDF model requires the prior estimation for each of the key durations of the variable termed RMED, the median annual maximum rainfall, over a 1-km grid of the UK. A new methodology for estimating this is being adopted.

In a pilot study, the new DDF model has been applied to two catchments in west Cumbria, the Derwent at Camerton (area 661.9 km^2) and the Leven at Newby Bridge (area 247.8 km^2), to estimate the frequency of the extreme event that caused widespread flooding in November 2009 (Stewart *et al.*, 2011). The variable *RMED* for the key durations was mapped using a new interpolation method that incorporates gridded (1-km resolution) values of the standard average annual rainfall (*SAAR*) as a predictor, as well as the *RMED* calculated from observations at gauged sites. The new DDF model was fitted at every point on a 1-km grid covering the two catchments, and used to estimate rainfall depths for the key durations and for return periods from 2 to 10 000 years at every grid point. To estimate the rarity of the catchment *areal* rainfall, a catchment-representative *point* rainfall of a particular duration and return period was first derived for each catchment: for each combination of duration and return period, the point rainfall depths were averaged across each catchment. These catchment-representative point rainfalls were then multiplied by the areal reduction factors presented in the FEH (Keers & Wescott, 1977) to give the catchment average rainfall of the appropriate return period and duration.

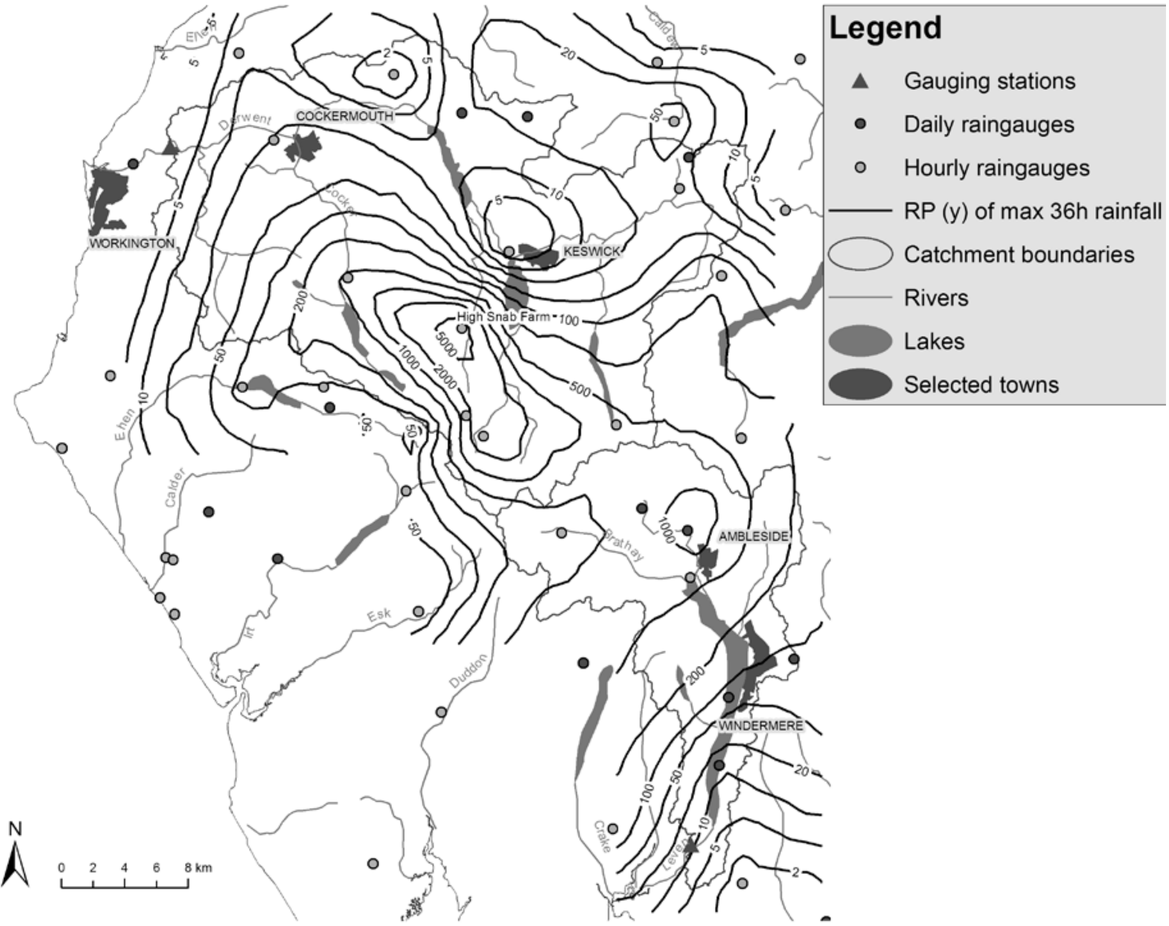

Fig. 2 Contour map of the estimated return period of the maximum 36-h rainfall depth recorded over west Cumbria during the event in November 2009.

The most extreme (rarest) rainfall recorded at raingauges at Seathwaite Farm and Honister Pass during the November 2009 event occurred over a 36-h period (Sibley, 2010). Figure 2 illustrates the estimated return period from the new model of the maximum 36-h rainfall recorded over the two catchments. The contours indicate that the highest return periods occur in the vicinity of the High Snab Farm raingauge, just to the north of the raingauges that recorded the highest rainfall depths, and show how extreme the event was over the Derwent catchment. The maximum 36-h rainfall over the Derwent catchment during the event was estimated at 155.7 mm from the available raingauges, and the associated return period for the catchment rainfall was assessed at 193 years by the new model.

Figure 3 shows a comparison of the frequency curves for catchment average rainfall for one of the catchments derived from the new DDF model and from the FEH model for the 36-h duration. It can be seen that the new model gives higher rainfall estimates than the FEH for return periods between 2 and 50 years, and lower estimates for return periods in excess of 50 years.

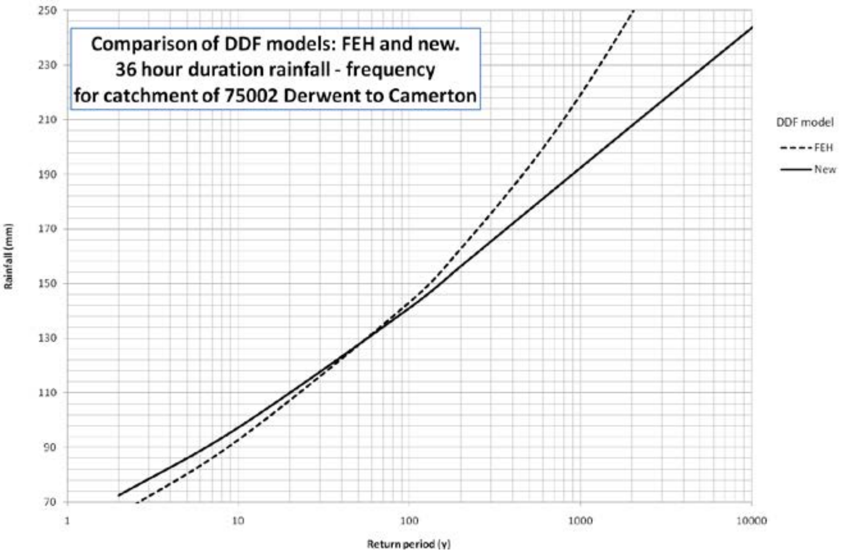

Fig. 3 Comparison of rainfall frequency curves derived from the new and FEH rainfall DDF models for the catchment of the Derwent to Camerton for a duration of 36 h.

NEXT STEPS

Work is continuing to explore the behaviour of the new rainfall DDF model in different parts of the UK and to compare the results with the FEH for the full range of durations and return periods to which the model is applicable. Until now, the focus of the research has been on return periods of over 100 years, which are relevant to fluvial flood risk management, but further exploration of the model results for shorter return periods is planned, particularly in southeast England where rainfall estimates from the FEH model for shorter durations have been questioned.

Other aspects of the model are also being considered, including the spatial resolution of the outputs. It is likely that a 1-km grid will be used as it was in the FEH rainfall model implementation, although the possibility of using a finer grid spacing in upland areas such as the Lake District will be evaluated.

Finally, as in the FEH and FSR models, areal reduction factors (ARFs) are used to convert point rainfall estimates to areal estimates. There is a general need to update the values of ARF since the current methodology dates back to 1975 and takes no account of possible variation with return period or geographical location.

Future applications of the new model

For hydrological design studies using rainfall–runoff modelling, the new DDF model will be incorporated into a revised software utility which will be released on an upgrade to the FEH CD-

ROM in the near future. Applications such as urban drainage design generally require rainfall frequency estimates for shorter durations and, although the finest temporal resolution of the new DDF model is currently 1 h, reflecting the data that were used in the analysis, further work will look at the feasibility of extrapolating to sub-hourly durations. This will allow the new model to be incorporated into an upgrade of the Hyrad system to allow post-event analysis of rainfall events identified by weather radar in urban areas. In the longer term, it would be preferable to develop a model specifically for shorter durations and return periods should the necessary data be available from recording raingauges and possibly weather radar.

CONCLUSIONS

The development of a new rainfall depth-duration-frequency (DDF) model has been described and examples of its application at individual points and over catchment areas have been presented. For other applications such as urban drainage modelling and compliance monitoring using weather radar, new software solutions are being explored. Possible future delivery mechanisms include the development of a web service to "plug in" to other software systems to provide rainfall frequency estimates for user-defined points or areas, or a more interactive "pay-per-view" web system.

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