Frequency analysis of extreme rainfall in Cumbria, 16–20 November 2009

E. J. Stewart, D. G. Morris, D. A. Jones and H. S. Gibson

ABSTRACT

Towards the end of November 2009, west Cumbria in northwest England experienced severe flooding which caused extensive damage and disruption throughout the region. The flooding was triggered by an exceptional rainstorm during which a record 316.4 mm of rainfall was recorded at Seathwaite Farm, Borrowdale over the 24-hour period up to 00:00 on 20th November. Drawing on the results of a recent project which has developed a new model of point rainfall depth-duration-frequency (DDF) for the UK, return periods are estimated for the highest point rainfall observations available for the Cumbrian event and compared with frequency estimates derived from the Flood Estimation Handbook rainfall model (Faulkner 1999). The spatial and temporal characteristics of the storm event are examined using data from the Environment Agency's raingauge network. For the two most affected rivers, the Derwent and the Leven, return periods of catchment rainfall are estimated for durations up to 96 hours.

Key words | depth-duration-frequency model, extreme rainfall, Flood Estimation Handbook, statistical frequency

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INTRODUCTION

Widespread floods were experienced in Northern Ireland, north Wales, northwest England and Scotland in November 2009 following a prolonged period of wet weather that included a new 24-hour rainfall maximum for a UK raingauge. The most serious effects occurred in west Cumbria from the 19th November onwards, with the towns of Cockermouth and Workington experiencing particularly severe flooding which inundated large numbers of properties and caused transport chaos. A police officer died in Workington after a road bridge collapsed. This paper considers the statistical frequency of some of the highest raingauge observations and derived catchment averages from the event in Cumbria, comparing return periods from a new model of rainfall depth-duration-frequency (DDF) (Stewart *et al.* 2010a) with results from the Flood Estimation Handbook (FEH) rainfall model (Faulkner 1999).

DETAILS OF THE RAINFALL EVENT IN NOVEMBER 2009

A warm, moist south-westerly airstream affected the UK between the 18th and 20th November 2009 which was associated with a very deep Atlantic depression between Scotland and Iceland tracking slowly north-eastwards (Met Office 2009). A weather front within this airstream became stationary over Cumbria and Northern Ireland and this, together with substantial orographic enhancement, produced many storm totals of greater than 50 mm. The most extreme rainfall depths were recorded across high ground in the Lake District, with hourly rainfall rates peaking at 16–17 mm h^{-1} on the 19th November (Sibley 2010). The weather system persisted for about 36 hours. During the event, the highest observation was at Seathwaite Farm in Borrowdale, with 316.4 mm of rainfall recorded over a 24-hour period. This is the highest officially recognised 24-hour rainfall total (recorded over any 24-hour period)

doi: 10.2166/nh.2012.033

ever recorded in the UK, exceeding the previous record of 279 mm of rainfall during the Martinstown storm of July 1955 (http://www.metoffice.gov.uk/climate/uk/extremes/); there is some evidence to suggest that the Martinstown figure should be revised upwards, however (Clark 2005). The official Martinstown total remains the highest recorded over a single rainfall day (09:00 to 09:00 GMT). It should be noted that the Seathwaite Farm 24-hour total exceeds the previous UK maximum for any two consecutive rainfall days (315 mm, also at Seathwaite Farm, on 4–5 December 1864; Eden & Burt 2010).

ASSESSING THE FREQUENCY OF EXTREME RAINFALLS

The UK is fortunate in having long records of raingauge observations going back, in many cases, to the 1860s when George Symons started to develop a network of rainfall monitors that became the British Rainfall Organisation (Pedgley 2010). However, it will not be possible to fully exploit this wealth of information as long as the majority of pre-1961 records remain to be digitised. Nevertheless, the UK has a long history of rainfall DDF modelling for the assessment of water resources, hydrological design and post-event analysis. Volume II of the Flood Studies Report (FSR; NERC 1975) presented a model of UK rainfall frequency that has had a worldwide influence, but was criticised for being over-generalised (Faulkner 1999). The FSR was superseded by the FEH (Institute of Hydrology 1999), which introduced a new set of procedures for the estimation of rainfall and flood frequency in the UK based on digital catchment information and the use of flexible regionalisation schemes.

This paper follows the convention used in the FSR and the FEH of referring to rainfall frequency in terms of return period T, in years. For statistics based on annual maxima, T is the average interval between years in which a specified rainfall value is exceeded. An event with a T-year return period has an annual exceedance probability of $1/T$.

Recent research under the Joint Environment Agency/Defra Flood and Coastal Risk Management R&D Programme has developed a new model of rainfall DDF applicable to the whole of the UK (Stewart *et al.* 2010a). The project was led by CEH and involved researchers from the Met Office and the Universities of Salford and Sheffield. The new model has been developed for rainfall durations from 1 hour to 8 days, and was commissioned in response to concerns expressed by reservoir engineers about the apparently high rainfall depth estimates produced by the FEH rainfall model when it was applied to return periods in excess of its recommended upper limit of 1,000 years. One particular aspect of the FEH model that was considered to be in need of revision was the form of the extrapolation used to provide the long return period rainfalls required for reservoir flood safety assessments (MacDonald & Scott 2001).

The new DDF model has been designed to provide rainfall estimates for return periods ranging from 2 to over 10,000 years, and it is proposed that it should eventually replace the FEH rainfall model for hydrological design and analysis in the UK. The project team was able to extend the dataset of annual maximum rainfall depths used in the FEH analysis in terms of both record length and the density of raingauge sites, particularly for sub-daily durations where the number of raingauges with suitable records was increased from 375 to 969. The basic approach mirrored that used in the FEH rainfall analysis, which adopted a two-stage index-flood methodology, and a number of key revisions were introduced.

Firstly, the simple standardisation used in the FEH, whereby annual maxima at each raingauge are divided by the at-site median value of the appropriate duration (*RMED*), was replaced by a revised standardisation designed to remove more of the location-dependent variation in the distribution of rainfall before combining data from networks of raingauges. The second stage in the FEH was the application of the Focused Rainfall Growth Extension (FORGEX) methodology (Faulkner 1999). The project has made a number of changes to FORGEX, most notably by using a new model of the spatial dependence in rainfall extremes that allows dependence to reduce gradually as return period increases. Also the FORGEX algorithm has been improved to give a better fit to the data points and to ensure more gradual variation between locations.

The new DDF model has been fitted to rainfall frequency curves produced by the revised FORGEX analysis for the full range of durations and return periods. With

14 parameters, it is more complex and flexible than the six-parameter FEH model. The new 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, in contrast to the exponential increase inherent in the FEH DDF model when extrapolated beyond a return period of 1,000 years.

The new DDF model was developed from the analysis of rainfall frequency curves centred on over 70 locations across the UK. Currently, the model can be applied by the CEH team at any point of interest whether it is a gauged site or not, provided that sufficient information is available to estimate the at-site *RMED* value for each of the 11 key durations used in the study. Plans are in place to generalise the model results across the UK and to develop a new software package to provide rainfall estimates focused on any location. This will require the production of a set of updated digital maps of *RMED*.

RETURN PERIOD ANALYSIS

In this paper, the new DDF model of Stewart *et al.* (2010a) is applied to a pilot region of west Cumbria. The model is used to assess the frequency of the highest point and catchment average rainfalls recorded over a range of durations during the extreme event of 16–20 November 2009, and the results are compared with return period estimates derived from the FEH model.

DATA

Data for the rainfall event itself were supplied by the Environment Agency and consisted of hourly depths from 69 tipping bucket raingauges (TBRs) and 1-day totals (measured from 09:00 to 09:00 GMT) from 39 daily gauges for the period 16–24 November 2009. Two individual TBR records, from the gauges at Seathwaite Farm and the Honister Pass, were studied in detail because they recorded the highest rainfalls during the November 2009 event. The locations of the two gauges are shown in Figure 1 and some information about the sites is provided in Table 1. The gauges are situated about 1.7 km apart in an area of very high standard average annual rainfall (*SAAR*). The Honister Pass raingauge is located at the top of the pass connecting the Buttermere valley with the Borrowdale valley; this means it generally records higher rainfall depths than the Seathwaite Farm gauge, which is situated in the Borrowdale valley. However, in the case of the extreme rainfall recorded in November 2009, the maximum 24-hour value recorded at Seathwaite Farm (316.4 mm) exceeded that recorded at Honister Pass by 15 mm.

As well as considering the highest point rainfalls recorded during the event, areal average rainfall was estimated for two catchments shown in Figure 1: the Derwent at Camerton (area 661.9 km^2) which was particularly badly affected by flooding and the Leven at Newby Bridge (area 247.8 km^2).

DETAILS OF THE RAINFALL EVENT

Using a two-stage procedure, the observed storm rainfall depths at the 69 hourly and 39 daily raingauges were interpolated on a 1 km square grid for each hour between 09:00 on 16 November and 09:00 on 24 November to form a time series of 192 hourly 1 km grids. The first stage involved, at each hour, interpolating between the hourly gauge values after first standardising them by dividing by their 1961–1990 *SAAR* value; at each grid point the interpolated values were converted to rainfall depth using the *SAAR* value for the grid point. The second stage brought in the information from any daily raingauges that were not located at the same site as an hourly gauge. For each 24-hour 09:00–09:00 period (rainfall day) the 24 hourly grids were summed and, at each daily gauge location, an adjustment factor (observed/gridded) was calculated. At each hourly gauge location the adjustment factor was set to 1. The combined set of daily and hourly gauge adjustment factors was then interpolated to form a 1 km adjustment factor grid. The final 1 hour grids were formed by multiplying each 1 hour grid by the adjustment factor grid applicable to that rainfall day. Both stages used the ArcGIS implementation of the natural neighbour interpolation method (Gold 1989).

Figure 2 shows the spatial distribution of the maximum 36-hour rainfall at each 1 km grid point. It indicates that the

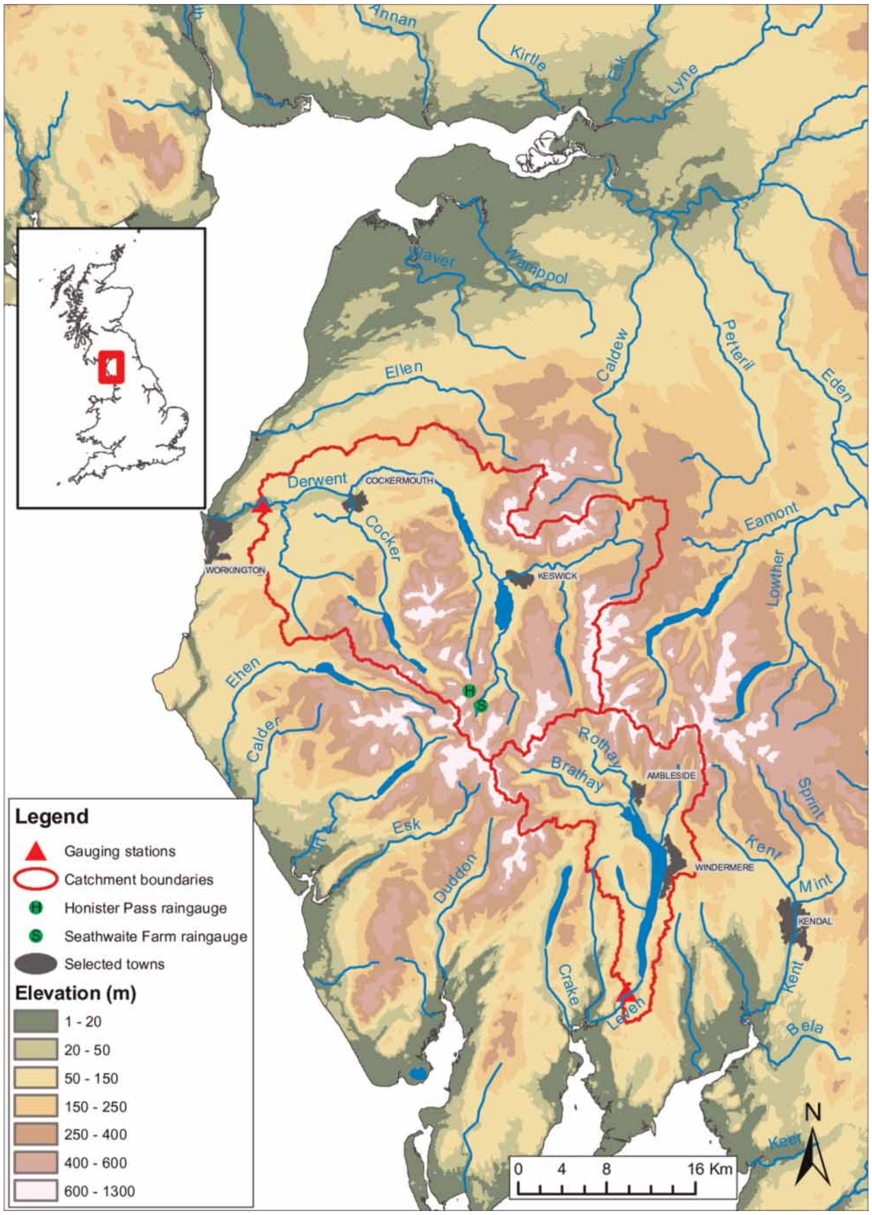

Figure 1 | Location map showing raingauges experiencing high rainfalls during the November storm and the two catchments studied in this paper.

Table 1 | Details of the featured raingauge sites

Gauge	Number	Easting	Northing	Altitude	*SAAR* 1961–1990 (mm)
Seathwaite Farm	592,448	3,235	5,121	129	3,137
Honister Pass	592,463	3,225	5,135	358	3,389

highest rainfall depths were recorded in the upper parts of the Derwent and Leven catchments. The map also shows that 36-hour rainfall depths of over 200 mm were widely spread across the Lake District.

Figures 3 and 4 show the hourly hyetographs for the two catchments, obtained by averaging the values at the 1 km

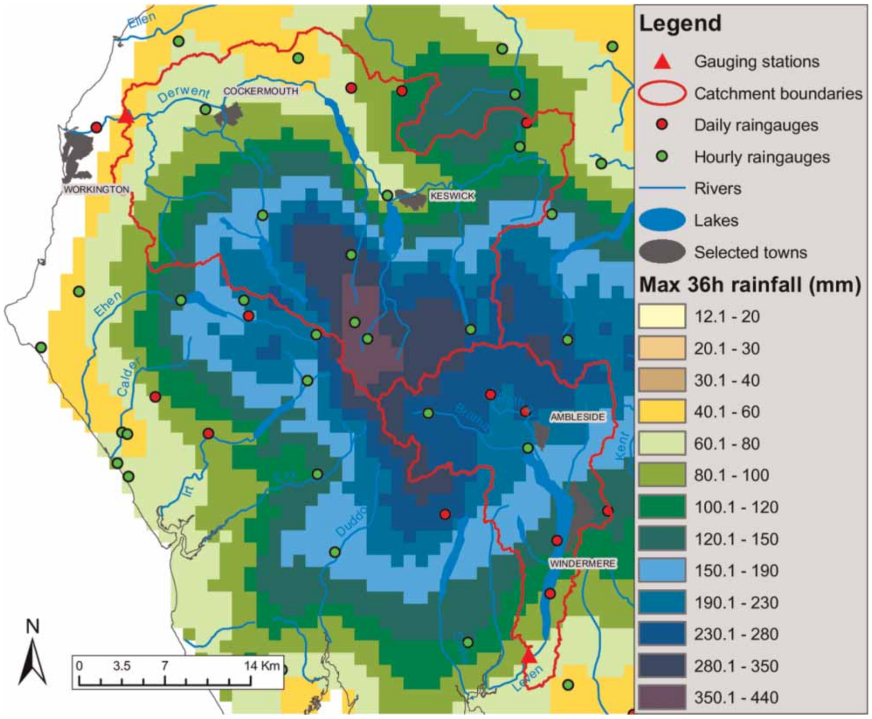

Figure 2 | Distribution of rainfall showing, for each point, the largest rainfall total experienced in any 36-hour period during the event, with the raingauges from which the distribution was estimated.

grid points within the catchment boundaries. While the most intense rainfall fell in the Derwent catchment (75,002), its areal average is lower due to the lower rainfall in the north and west (Figure 2).

FITTING THE NEW DDF MODEL

In the first stage of the analysis, the new DDF model was fitted at the two selected raingauge sites detailed in Table 1.

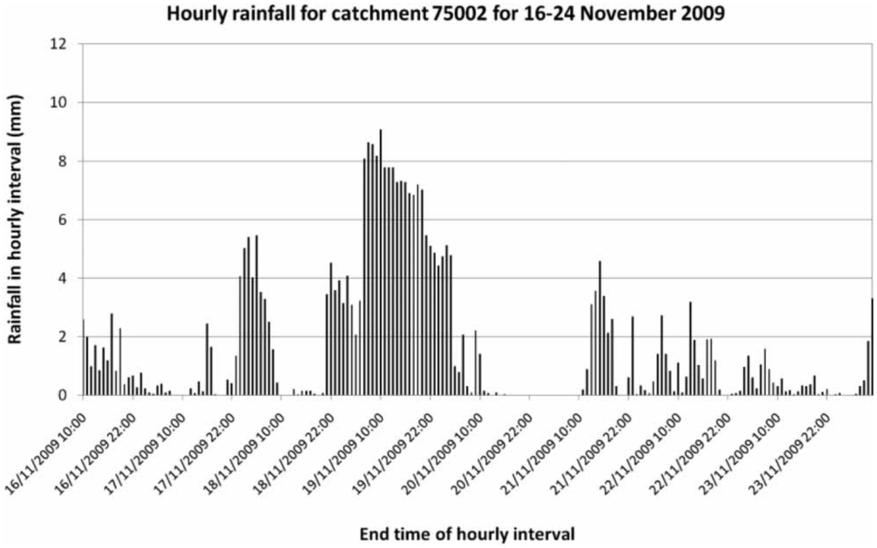

Figure 3 | Areal average hyetograph for the Derwent catchment.

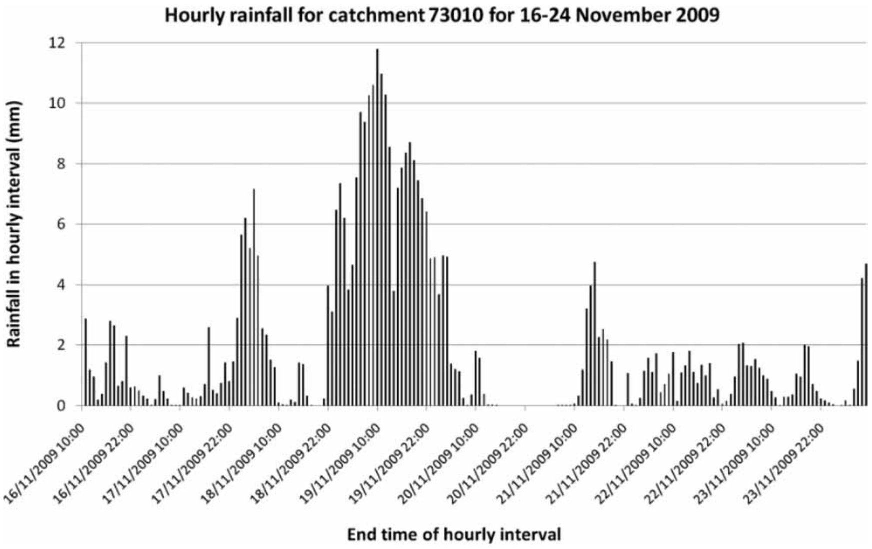

Figure 4 | Areal average hyetograph for the Leven catchment.

The results are summarised here and further details are given by Stewart *et al.* (2010b). The second stage of the analysis involved fitting the new DDF model at every point on a 1 km grid covering the catchments of the Derwent and the Leven to allow the rarity of the catchment average rainfalls to be estimated. Both stages made use of an extensive dataset of annual maxima for the UK which was constructed during the Defra project (Stewart *et al.* 2010a). This comprises records of at least nine annual maxima for over 6,500 daily raingauges and 969 hourly gauges for 11 key durations ranging from 1 hour to 8 days. The earliest records date from 1,853 and the annual maxima go up to 2006; the dataset used to fit the model therefore does not include any data from the November 2009 event.

RMED estimation and mapping

The first step in the model fitting requires estimates of *RMED*, the median annual maximum rainfall at the site of interest which has a return period of 2 years, for each of the 11 key durations. In the case of the Honister Pass and Seathwaite Farm raingauges, the *RMED* values were estimated directly from the hourly and daily records available at those sites. The *RMED* values for Honister Pass were found to be substantially higher than those derived from the FEH DDF model at all durations, and this is thought to reflect the lower density of raingauge data available at the time of the FEH analysis. The values of *RMED* computed for the Seathwaite Farm site were closer to those derived from the FEH model. Further details are given by Stewart *et al.* (2010b).

In order to fit the new DDF model across the two selected catchments, 1 km grids of *RMED* were established for the same key durations as used in the individual site fitting. The method used differed from the georegression applied in the FEH analysis (Faulkner 1999), instead using the spatial variation of *SAAR* across the region and relating all other durations to the *RMED* value for the 24-hour duration ($RMED_{24h}$). Details of the method used are given in the Appendix (available online at http://www.iwaponline.com/nh/043/033.pdf). As an example, the final interpolated $RMED_{24h}$ grid is shown in Figure 5, indicating that the highest values of over 140 mm occur in the upper Derwent catchment.

Revised FORGEX analysis and DDF model fitting

Point rainfall frequency

The second step of the model-fitting procedure involves application of the revised FORGEX procedure described by Stewart *et al.* (2010a). Initially, an analysis of the Honister Pass and Seathwaite Farm raingauge sites was carried out using *RMED* values derived empirically from the available

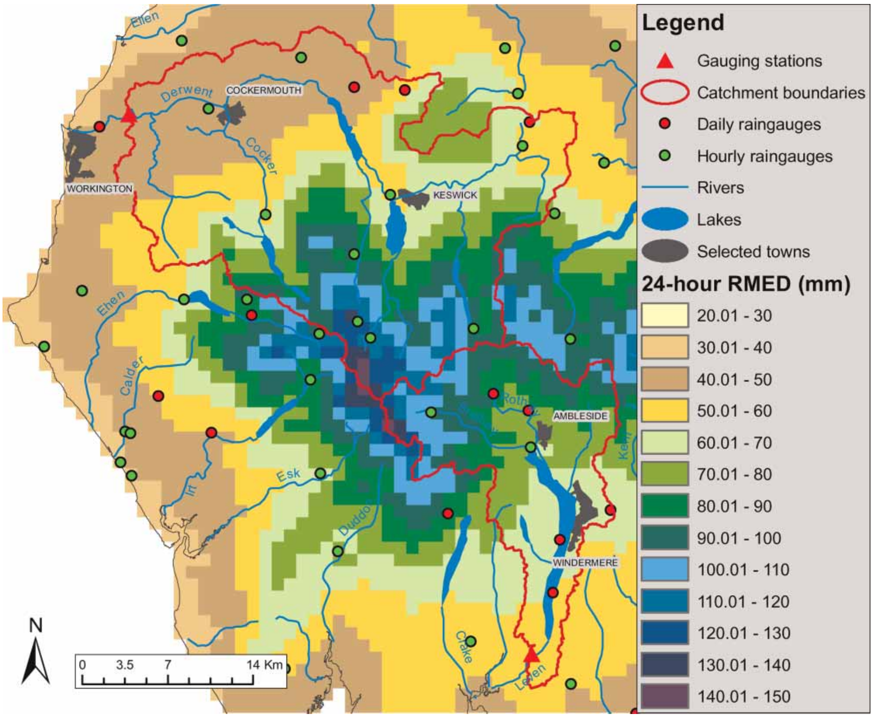

Figure 5 | Variation of the median annual maximum 24-hour rainfall across the region using values from the $RMED_{24h}$ grid.

data, and the resulting frequency curves were compared to those derived from the original FEH FORGEX methodology: these results are reported by Stewart *et al.* (2010b). Figure 6 gives an example comparison for the 24-hour duration focused on Honister Pass. The FEH FORGEX curve, produced using the FEH dataset, is shown in red and the revised curve (in green) lies above it, indicating that the new method together with the updated dataset produces rainfall estimates that are higher than the FEH method for a given return period. Stewart *et al.* (2010a) however found that, for most of the UK (except Scotland), rainfall estimates from the new model tend to be lower than those from the FEH, especially at high return periods. The unusual results at Honister Pass are thought to be mainly due to the improved estimation of *RMED* through the inclusion of data from the raingauge site.

Figure 7 shows a comparison between the FEH FORGEX and revised FORGEX curves for the 24-hour duration focused on Seathwaite Farm. The revised curve (shown in green) lies to the right of the FEH FORGEX curve, indicating that the revised method produces lower rainfall estimates than the FEH method for a given return period. This result is typical of the sites tested throughout England, Wales and Northern Ireland (Stewart *et al.* 2010a).

The revised FORGEX frequency curves were adjusted for discretisation (see Stewart *et al.* 2010a, Appendix J, for further details) and then used to fit the new DDF model at the two raingauge locations.

Catchment average rainfall frequency

In an extension of the method applied for Stewart *et al.* (2010b), the revised FORGEX procedure was applied to points on a 1 km grid covering the study catchments using the gridded values of *RMED* for durations from 1 to 192 hours. The results were then fed into programs for fitting the new DDF model. This has allowed the assessment of the return period of rainfall observations made during the November 2009 event for point rainfalls at further locations and for catchment average rainfalls.

The catchment average rainfall frequency was assessed by using the fitted DDF model to estimate rainfall depth for many combinations of duration (ranging from 1 to 192 hours) and return period (from 2 to 10,000 years) at every grid point

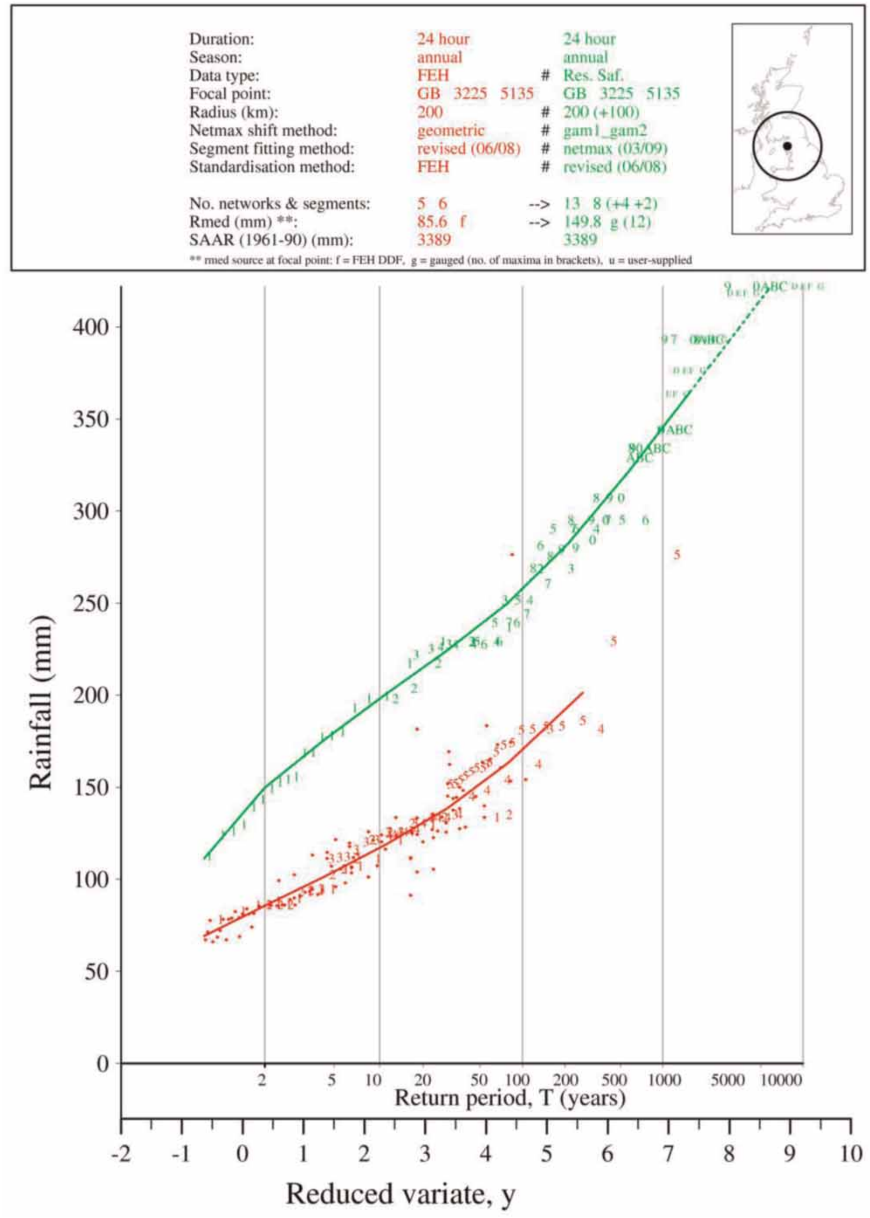

Figure 6 | Comparison of the FEH FORGEX (red) and revised FORGEX methods (green) for the 24-hour duration focused on the Honister Pass raingauge site.

within each catchment. For each combination of duration and return period, these modelled rainfall depths were averaged across all the grid points within each catchment to give an average *point* rainfall of a specified duration and return period for that catchment. Finally, the areal reduction factors presented in the FEH (which originated in the FSR analysis and were generalised by Keers & Wescott 1977) were applied to the average point rainfalls to give the catchment average rainfall of the appropriate return period and duration.

RESULTS

Point rainfall

For the Honister Pass and Seathwaite Farm raingauge sites, maximum rainfall depths for durations from 1 hour to 4 days were abstracted from the hourly and daily rainfall data over the period 16–20 November 2009 and the return period estimates derived from the FEH DDF model software on the

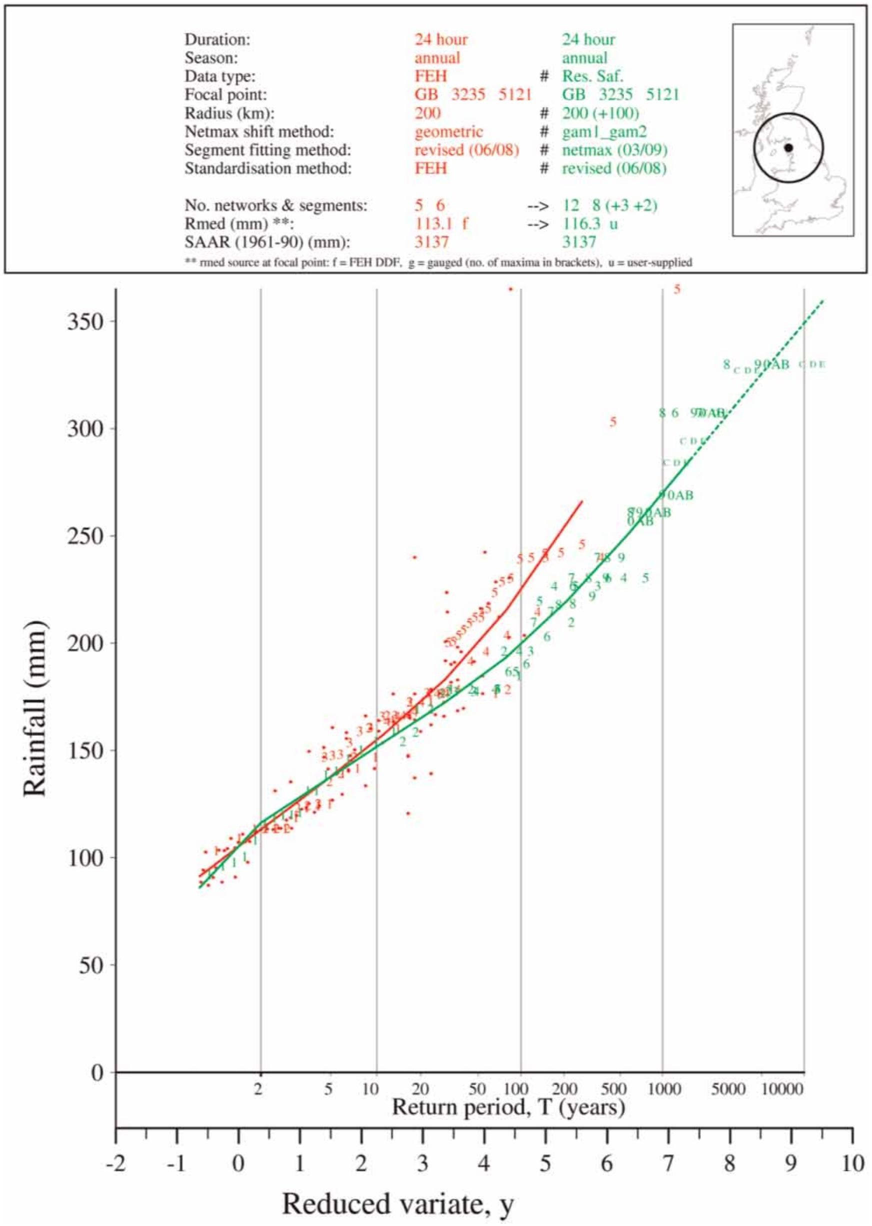

Figure 7 | Comparison of the FEH FORGEX (red) and revised FORGEX methods (green) for the 24-hour duration focused on the Seathwaite Farm raingauge site.

FEH CD-ROM (CEH 2009) and the new DDF model were compared. Table 2 shows that the return periods estimated by the new DDF model for Honister are substantially lower than those produced by the FEH model at all durations. Table 3 shows comparative return periods from the two models for the Seathwaite Farm site, and here the estimated return periods from the new model exceed those from the FEH model for all the durations studied. At Seathwaite Farm, the duration with the highest return period was 37 hours (401.6 mm, 4,202 years as assessed using the new model).

Figure 8 shows the spatial pattern of the maximum rainfall total over 36 hours with a return period of 1,000 years, as estimated by the new DDF model. This is directly comparable with Figure 2. Figure 9 shows the estimated return period of the 36-hour maximum totals for the November

Table 2 | Comparison of return period estimates for the November 2009 event at Honister Pass

		Return period estimate (years)	
Duration (h)	**Rainfall (mm)**	**FEH DDF model**	**New DDF model**
6	82.2	36	3
12	157.6	172	12
24	301.4	1,234	396
36	376.6	1,977	1,013
48	391.0	1,449	795
72 (3 rain days)	454.4	3,240	1,659
96 (4 rain days)	489.8	3,552	1,143

Table 3 | Comparison of return period estimates for the November 2009 event at Seathwaite Farm

		Return period estimate (years)	
Duration (h)	**Rainfall (mm)**	**FEH DDF model**	**New DDF model**
6	102.4	22	51
12	189.2	70	332
24	316.4	158	1,862
36	392.6	172	3,656
48	405.0	93	1,973
72 (3 rain days)	456.4	132	3,380
96 (4 rain days)	495.0	109	2,984

2009 event. The highest return periods occur in the vicinity of the High Snab Farm raingauge.

Catchment average rainfall

Table 4 shows values of the maximum 36-hour catchment average rainfall for the two catchments, together with the return periods estimated for these using the FEH DDF model and the new DDF model. The comparison indicates that the new DDF model assigns a slightly higher return period to the 36-hour average rainfall over the Derwent catchment (i.e. assesses the event as less frequent) than the FEH model. For the maximum average 36-hour rainfall over the Leven, the return period derived from the new model is considerably greater than that of the FEH model.

Results from the new DDF model for the maximum catchment average rainfall over durations ranging from 1 to 100 hours are summarised in Figure 10. This shows

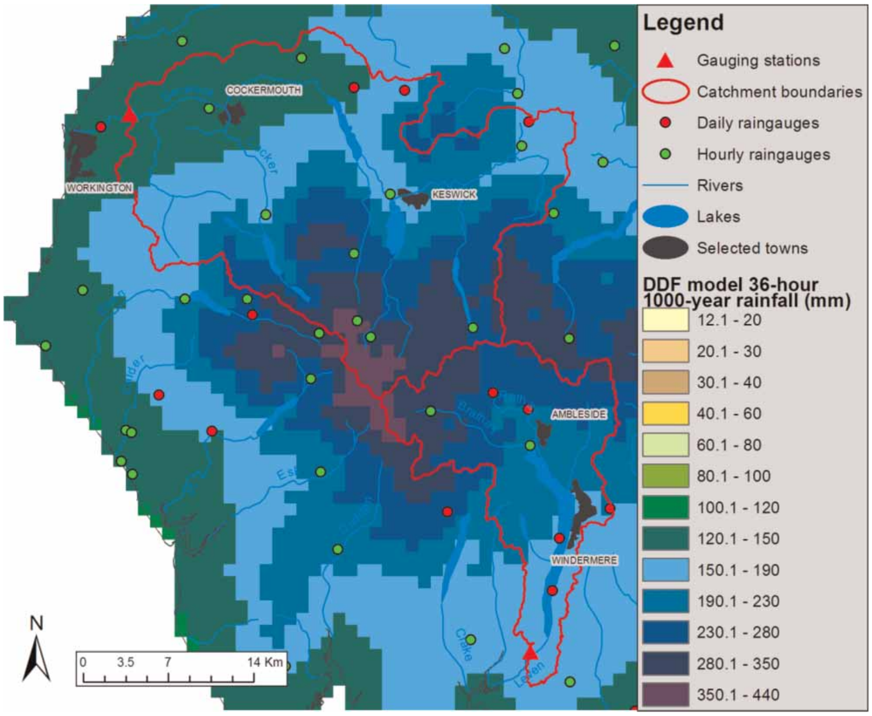

Figure 8 | Results from the DDF model showing the estimated value of the annual maximum 36-hour rainfall with a return period of 1,000 years for any point.

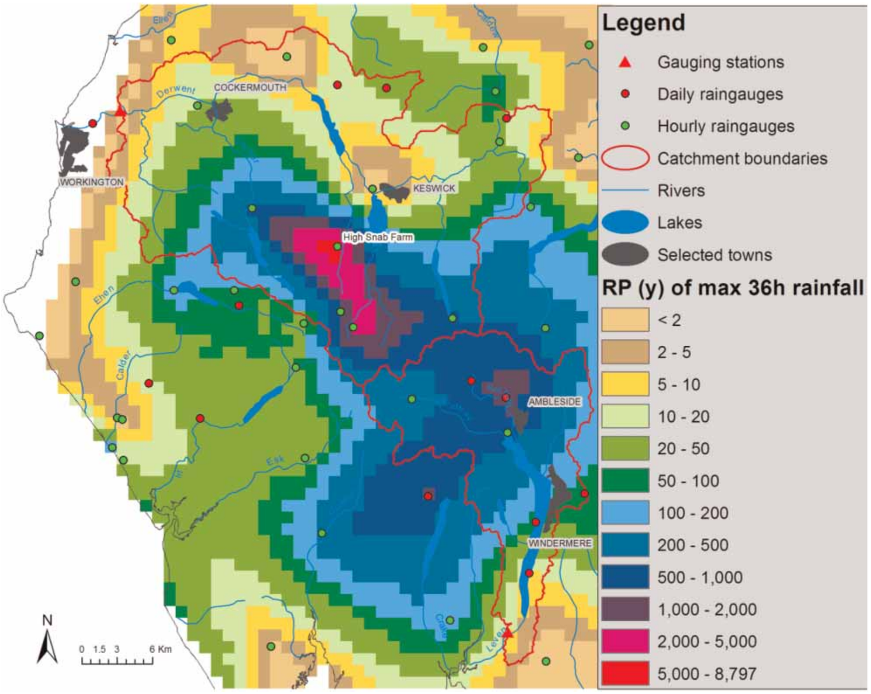

Figure 9 | Estimated return period of the maximum 36-hour total rainfall experienced at each point in the region.

Table 4 | Comparison of return period estimates for maximum 36-hour catchment average rainfall

			Return period estimate (years)	
Catchment	**Area (km^2)**	**Maximum 36-hour catchment Average rainfall (mm)**	**FEH DDF model**	**New DDF model**
75,002 Derwent to Camerton	661.9	155.7 (to 0,800 on 20/11/2009)	157	193
73,010 Leven to Newby Bridge	247.8	200.3 (to 0,900 on 20/11/2009)	185	485

that the highest return periods for both catchments occur at around a duration of 54 hours.

DISCUSSION

It is important to realise that there is considerable uncertainty associated with the frequency estimates from the new DDF model; they should therefore be treated with some caution, particularly at very high return periods. Although a well-founded assessment of the uncertainty of the estimates produced by the new DDF model was outside the scope of the Defra project within which it was developed, some general comments can be made. The basis of the model is the production of estimates that reflect the historical data in a region centred on a target location, and thus 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. However, it is sometimes the case that the raingauge network does not adequately capture the spatial and temporal characteristics of individual extreme storm events, as for example in the Martinstown storm of 1955 (Clark 2005). Advances have been made in the use of weather radar to characterise more recent storm events such as the Boscastle storm of

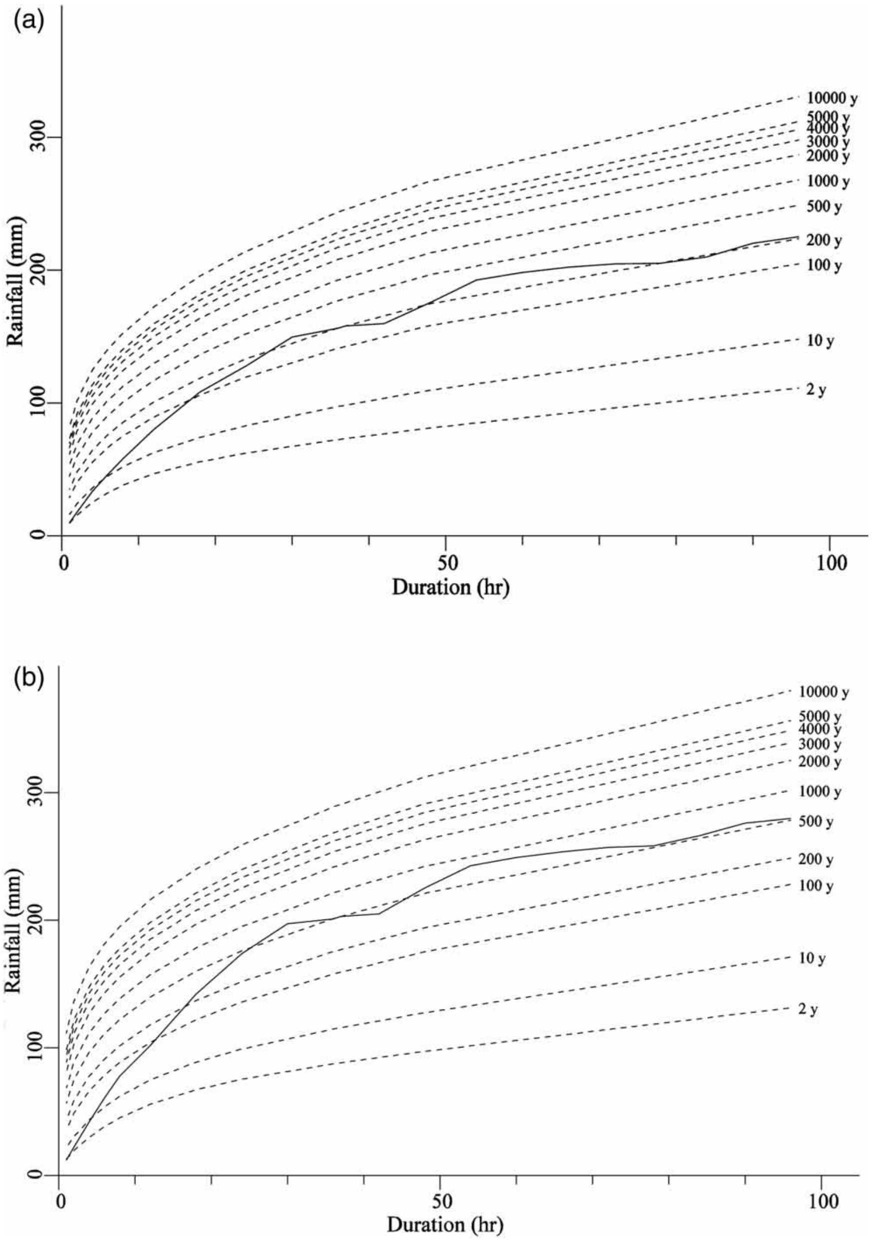

Figure 10 | DDF curves of catchment average rainfall (dashed lines), together with the maximum catchment average rainfall of any duration for the event of November 2009, for (a) the Derwent catchment and (b) the Leven catchment.

2004 (Golding *et al.* 2005), but the reconciliation of quantitative rainfall estimates from raingauges and radar remains a practical problem. Work is continuing to develop ways to incorporate non-systematic rainfall measurements into the modelling process and thus to incorporate information for known extreme events that it has not been possible to include so far.

- Other important aspects of uncertainty in the results from the new DDF model arise from two sources:estimates of *RMED* for durations from 1 hour to 8 days: uncertainties here have a multiplicative effect in the DDF model and they arise both from the limited record lengths available at gauged locations and from interpolation to ungauged points; and

- extrapolation within the model to very high return periods: uncertainties here derive from both the form of extrapolation function used and the limited information, derived from network maxima, to which such functions are fitted.

Work may be undertaken to approximate the combined effects of these uncertainties, but the general approach taken within previous FEH work has been to concentrate on providing best estimates for rare flood and rainfall events.

The results of this study suggest that although the FEH and the new DDF models assign considerably different frequencies to the highest point rainfalls recorded during the extreme event over Cumbria in November 2009, the differences between the return periods of areal average rainfalls estimated over two example catchments are smaller in magnitude. The analysis demonstrates that the estimation of the spatial variability of *RMED*, the median annual maximum rainfall, has a profound effect on the frequency estimates resulting from both models. A key advantage of the new DDF model is that it is based on a denser set of hourly raingauge records than was available at the time of the FEH analysis. In time, it will therefore be possible to produce better maps of *RMED* so that the new model can be generalised across the UK.

Work by Stewart *et al.* (2010a) demonstrated that differences in frequency estimates derived from the two models are primarily due to differences in model structure and improvements in *RMED* estimation. Hence it is not thought that the results presented here are indicative of general changes with time in UK rainfall frequency, although this question remains to be explored. For example, Burt & Ferranti (2010) present evidence to suggest that the 1980s and 1990s saw an increase in heavy rainfalls occurring in winter in northern England, and a corresponding decrease in summer.

CONCLUSIONS

Application of a new model of rainfall DDF to the highest-point and catchment-average rainfall depths recorded during the extreme storm in Cumbria in November 2009 produces higher return period estimates (i.e. lower frequency) than those estimated using the FEH DDF model. Although the new model makes use of an updated set of annual maximum rainfall depths from raingauges across the UK, this result is largely due to the improved density of hourly data and improvements to the model, rather than being indicative of any recent changes or trends in rainfall frequency. An analysis of two individual raingauge records indicates that the maximum 36-hour point rainfall recorded during the event has a return period of about 1,000 years at the Honister Pass raingauge and about 3,700 years at the Seathwaite Farm raingauge. The corresponding 36-hour areal average rainfall for the catchment of the River Derwent to Camerton has been assessed as having a return period of around 200 years, reflecting the fact that the rainfall over the catchment was extremely variable in space. The maximum 36-hour rainfall in the Leven catchment was less spatially variable and is assessed as having a return period of around 500 years.

An important finding of this analysis is the large spatial variation in the return period of the storm over the Derwent catchment. Although the maximum 36-hour catchment average rainfall has been assessed as having a return period of 193 years, there is a spatial variation within the catchment from under 2 years to nearly 9,000 years (Figure 9). A companion paper (Miller *et al.* in press) estimates the return period of the November 2009 flood peak on the Derwent at Camerton to be 2,102 years, a figure which at first may seem incompatible with the 193-year rainfall return period. However, it seems likely that the high rainfall upstream of the lakes gave rise to an atypical hydrological response (Miller *et al.* in press), something which would not have occurred if the return period had been a uniform 193 years over the catchment. This shows the importance of being able to estimate rainfall frequency throughout a catchment, not simply in terms of a catchment average.

ACKNOWLEDGEMENTS

The development of the new rainfall DDF model was funded by Defra under the Joint Environment Agency/Defra Flood and Coastal Risk Management R&D Programme (contract WS 194/2/39). Data for the analysis described in this paper were supplied by the Environment Agency. The 1:50k watercourse network and catchment boundaries shown in Figures 1, 2, 5, 8 and 9 are copyright of NERC (CEH). Contains Ordnance Survey data © Crown copyright and database rights 2012.

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First received 1 February 2011; accepted in revised form 28 October 2011. Available online 3 May 2012