

Article (refereed) - postprint

Stewart, E.J.; Morris, D.G.; Jones, D.A.; Gibson, H.S.. 2012 Frequency analysis of extreme rainfall in Cumbria, 16-20 November 2009.

© Centre for Ecology and Hydrology 2012

This version available <http://nora.nerc.ac.uk/16377/>

NERC has developed NORA to enable users to access research outputs wholly or partially funded by NERC. Copyright and other rights for material on this site are retained by the rights owners. Users should read the terms and conditions of use of this material at <http://nora.nerc.ac.uk/policies.html#access>

This document is the author's final manuscript version of the journal article, incorporating any revisions agreed during the peer review process. Some differences between this and the publisher's version remain. You are advised to consult the publisher's version if you wish to cite from this article.

The definitive peer-reviewed and edited version of this article is published in *Hydrology Research*, 43 (5). 649-662. [10.2166/nh.2012.033](https://doi.org/10.2166/nh.2012.033) and is available at www.iwapublishing.com.

Contact CEH NORA team at
noraceh@ceh.ac.uk

Frequency analysis of extreme rainfall in Cumbria 16-20 November 2009

E. J. Stewart, D. G. Morris, D. A. Jones, H. S. Gibson,
Centre for Ecology & Hydrology,
Wallingford,
Oxfordshire
OX10 8BB
Tel: +44 (0)1491 692229
Fax: +44 (0)1491 692424
Email: ejs@ceh.ac.uk

ABSTRACT

Towards the end of November 2009, west Cumbria in north-west 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.

Keywords

Extreme rainfall, depth-duration-frequency model, Flood Estimation Handbook, statistical frequency

INTRODUCTION

Widespread floods were experienced in Northern Ireland, north Wales, north-west 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 (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) 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/>), although there is some evidence to suggest that the Martinstown figure should be revised upwards (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 and 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 Organization (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 depth-duration-frequency (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 depth-duration-frequency (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 revisiting was the form of the extrapolation used to provide the long return period rainfalls required for reservoir flood safety assessments (MacDonald and 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 used 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 6-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 1000 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 16th to 20th 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 from the 16th to the 24th 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 Fig. 1 and some information about the sites is given in Table 1. The gauges are situated about 1.7 km apart in an area of very high average annual rainfall (*SAAR*). The Honister Pass raingauge is located at the top of the pass connecting the Buttermere valley with the Borrowdale valley, which results in it generally recording 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 Fig. 1: the Derwent at Camerton (area 661.9 km²) which was particularly badly affected by flooding, and the Leven at Newby Bridge (area 247.8 km²).

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 16th November and 09:00 on 24th 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 standard annual average rainfall (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. Then the combined set of daily and hourly gauge adjustment factors was 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 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 grid points within the catchment boundaries. Whilst the most intense rainfall fell in the Derwent catchment (75002), its areal average is lower due the lower rainfall in the north and west (Fig. 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. 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 1853 and the annual maxima go up to 2006, and thus the dataset used to fit the model 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. As an example, the final interpolated $RMED_{24h}$ grid is shown in Fig. 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 data, and the resulting frequency curves were compared with 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. However, Stewart *et al.* (2010a) 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 hour to 192 hours) and return period (from 2 years to 10,000 years) at every grid point 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 from 16th to 20th November 2009 and the return period estimates derived from the FEH DDF model software on the 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, 4202 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 1000 years, as estimated by the new DDF model. This is directly comparable with Fig. 2. Figure 9 shows the estimated return period of the 36-hour maximum totals for the November 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 Fig. 10. This shows 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 and therefore they should 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 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.
- 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 might 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, and thus, in time, it will 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 depth-duration-frequency 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 1000 years at the Honister Pass raingauge and about 3700 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 9000 years (Fig. 9). A companion paper (Miller *et al.* 2011) estimates the return period of the November 2009 flood peak on the Derwent at Camerton to be 2102 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.* 2011), 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.

REFERENCES

Burt, T. P. & Ferranti, E. J. S. 2010 Changing patterns of heavy rainfall in upland areas: a case study from northern England. *Int. J. Climatol.* (2010) DOI: 10.1002/joc.2287

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

Clark, C. 2005 The Martinstown storm 50 years on. *Weather*, **60**, 9, 251-257.

Eden, P. & Burt, S. 2010 Extreme rainfall in Cumbria, 18-20 November 2009. *Weather*, **65**, 1, 14.

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

Gold, C. M. 1989 Surface interpolation, spatial adjacency and GIS. In: J. Raper (ed.) *Three Dimensional Applications in Geographical Information Systems*, 21-35. Taylor and Francis.

Golding, B., Clark, P. & May, B. 2005 The Boscastle flood: Meteorological analysis of the conditions leading to flooding on 16 August 2004. *Weather*, **60**, 8, 230-235.

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

Keers, J. F. & Wescott, P. 1977 A computer-based model for design rainfall in the United Kingdom. *Met Office Scientific Paper No. 36*, HMSO, London.

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.

Met Office 2009 *Floods in Cumbria – November 2009*.

<http://www.metoffice.gov.uk/climate/uk/interesting/nov2009/>

Miller, J. D., Kjeldsen, T.K., D., Hannaford, J. & Morris, D. G. 2011 An assessment of the magnitude and rarity of the November 2009 floods in Cumbria, UK. Accepted for publication in *Hydrology Research*.

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

Pedgley, D. E. 2010 The British Rainfall Organization, 1959-1919. *Weather*, **65**, 5, 115-117.

Sibley, A. 2010 Analysis of extreme rainfall and flooding in Cumbria 18-20 November 2009. *Weather*, **65**, 11, 287-292.

Stewart, E. J., Jones, D. A., Svensson, C., Morris, D. G., Dempsey, P., Dent, J. E., Collier, C. G. & Anderson, C. W. 2010a Reservoir Safety – Long return period rainfall (two volumes). *R&D Technical Report WS 194/2/39/TR*, Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme.

Stewart, E. J., Morris, D. G., Jones, D. A. & Spencer, P. S. 2010b Extreme rainfall in Cumbria, November 2009 – an assessment of storm rarity. *Proc. BHS Third International Symposium*, Managing Consequences of a Changing Global Environment, Newcastle 2010
<http://www.ceg.ncl.ac.uk/bhs2010/>

APPENDIX

The fitting of the new DDF model requires estimates of *RMED*, the median annual maximum rainfall with an associated return period of 2 years, for a number of key durations to be available at every site of interest. Grids of *RMED* at a resolution of 1 km were established over the two catchments of interest for durations of 1, 2, 4, 6, 12, 18, 24, 48, 96 and 192 hours. These were for what are termed “fully sliding” durations – *i.e.* annual maxima that would have been obtained from continuously recording raingauges, as opposed to annual maxima extracted from gauges recording at discrete hourly or daily intervals – and their computation required the preliminary step of multiplying the observed hourly or daily-based annual maxima by an appropriate discretisation conversion factor (see Table J.5 in Stewart *et al.*, 2010a).

The first grid to be derived was for 24-hour duration (*RMED*_{24h}), using data from all available gauges, both hourly and daily. Using only gauges in the Cumbria area, the following regression equation was derived, relating *RMED*_{24h} to 1961-90 standard annual average rainfall (*SAAR*) in mm:

$$\ln(RMED_{24h}) = -2.656 + 0.9169 \times \ln(SAAR) \quad (1)$$

This relationship was based on 166 gauges and has a correlation coefficient of 0.969. Equation 1 was applied at all locations on a 1-km grid covering Cumbria to produce an initial *RMED*_{24h} grid. A correction grid was derived by interpolating the factorial residuals (*RMED*_{24h} from observations / *RMED*_{24h} from Eqn. 1) at all gauges, using the ArcGIS implementation of inverse distance weighting interpolation. The final *RMED*_{24h} grid was produced by multiplying the initial grid by the correction grid.

RMED grids for other durations (for *nn* hours) were derived by working in terms of the ratio of *RMED*_{nnh} to *RMED*_{24h} at each gauge. Hourly gauges were used for durations

below 24 hours, and daily gauges for durations above. A regression equation for the Cumbria area was established for each duration, of the form

$$\ln(RMED_{nh} / RMED_{24h}) = a + b \times \ln(SAAR) , \quad (2)$$

where the values of the coefficients a and b are as shown in Table A1.

As for the $RMED_{24h}$ grid, grids of the ratio for each duration were established as the product of a regression equation grid and a correction grid. Finally, each of these grids was multiplied by the $RMED_{24h}$ grid to obtain the $RMED$ grid for each duration.

Table A1 Regression coefficients for the $RMED$ ratio in equation (2)

Duration	a	b
(h)		
1	2.103	-0.4836
2	0.9918	-0.2820
4	0.1991	-0.1262
6	-0.1635	-0.05062
12	-0.2005	-0.003355
18	-0.08146	0.0
48	-0.2700	0.06800
96	-0.2392	0.1005
192	-0.2581	0.1509

Table 1 Details of the featured raingauge sites

Gauge	Number	Easting	Northing	Altitude	SAAR 1961-1990 (mm)
Seathwaite Farm	592448	3235	5121	129	3137
Honister Pass	592463	3225	5135	358	3389

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

Duration (h)	Rainfall (mm)	Return period estimate (years)	
		FEH DDF model	New DDF model
6	82.2	36	3
12	157.6	172	12
24	301.4	1234	396
36	376.6	1977	1013
48	391.0	1449	795
72 (3 rain days)	454.4	3240	1659
96 (4 rain days)	489.8	3552	1143

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

Duration (h)	Rainfall (mm)	Return period estimate (years)	
		FEH DDF model	New DDF model
6	102.4	22	51
12	189.2	70	332
24	316.4	158	1862
36	392.6	172	3656
48	405.0	93	1973
72 (3 rain days)	456.4	132	3380
96 (4 rain days)	495.0	109	2984

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

Catchment	Area (km²)	Maximum 36-hour catchment average rainfall (mm)	Return period estimate (years)	
			FEH DDF model	New DDF model
75002 Derwent to Camerton	661.9	155.7 (to 0800 on 20/11/2009)	157	193
73010 Leven to Newby Bridge	247.8	200.3 (to 0900 on 20/11/2009)	185	485

Figure Captions

- Figure 1 Location map showing raingauges experiencing high rainfalls during the November storm and the two catchments studied in this paper
- 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
- Figure 3 Areal average hyetograph for the Derwent catchment
- Figure 4 Areal average hyetograph for the Leven catchment
- Figure 5 Variation of the median annual maximum 24-hour rainfall across the region using values from the *RMED_{24h}* grid
- 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
- 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
- Figure 8 Results from the DDF model showing the estimated value of the annual maximum 36-hour rainfall with a return period of 1000 years for any point
- Figure 9 Estimated return period of the maximum 36-hour total rainfall experienced at each point in the region
- 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

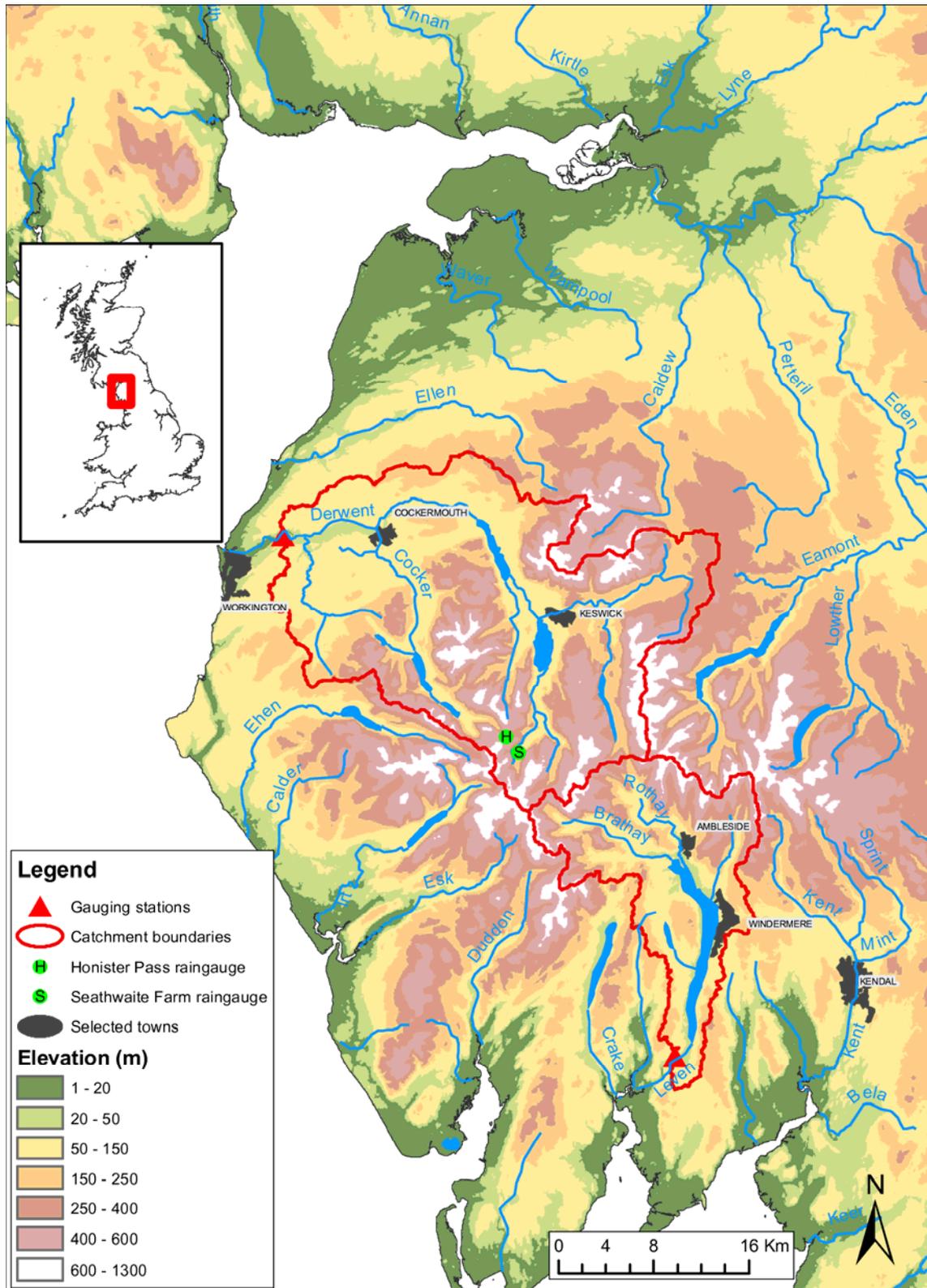


Figure 1 Location map showing raingauges experiencing high rainfalls during the November storm and the two catchments studied in this paper

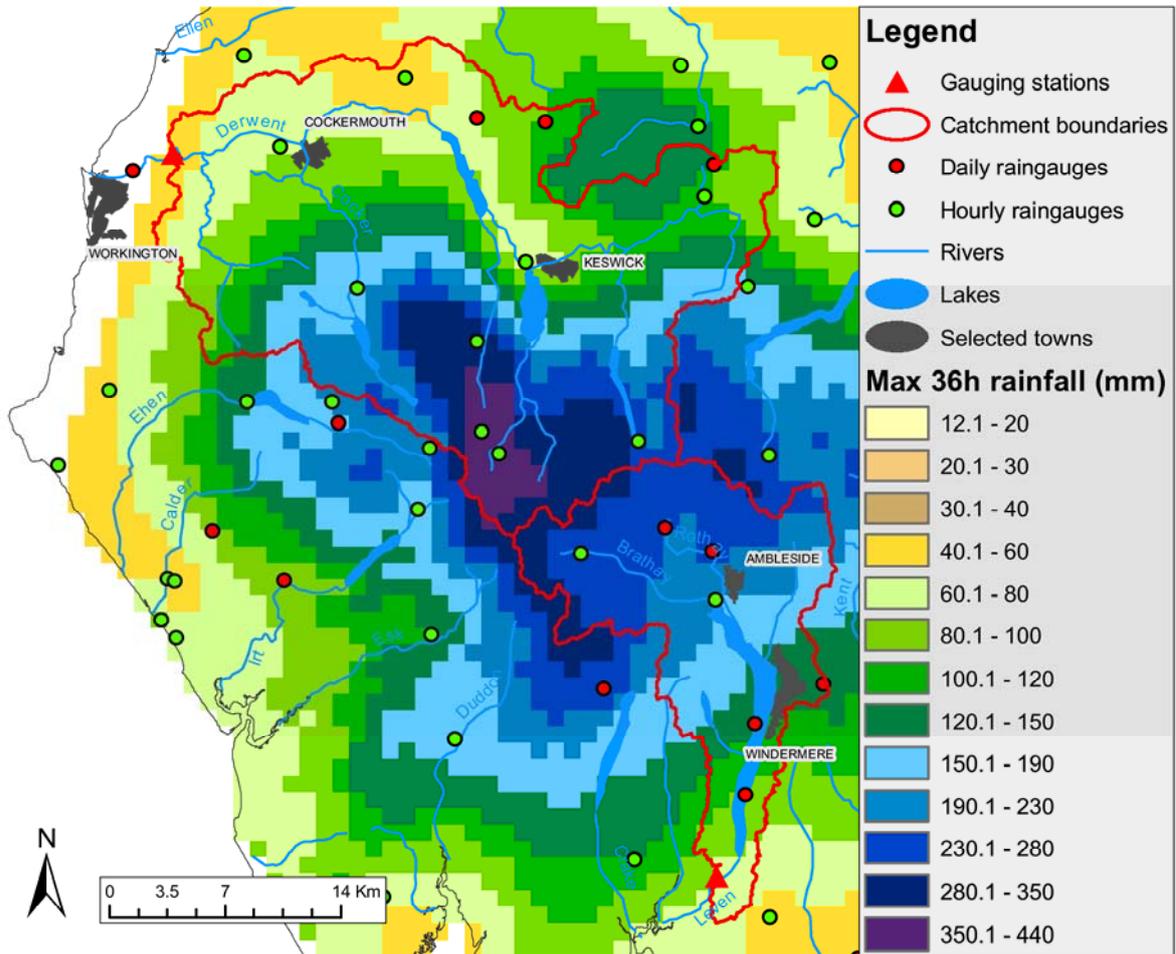


Figure 2 Distribution of rainfall showing, for each point, the largest rainfall total experienced in any 36-hour period during the event, with the raingauges from which the distribution was estimated. (Over this area, the end-time of the maximum 36-hour rainfall ranged from 02:00 to 12:00 on 20/11/2009)

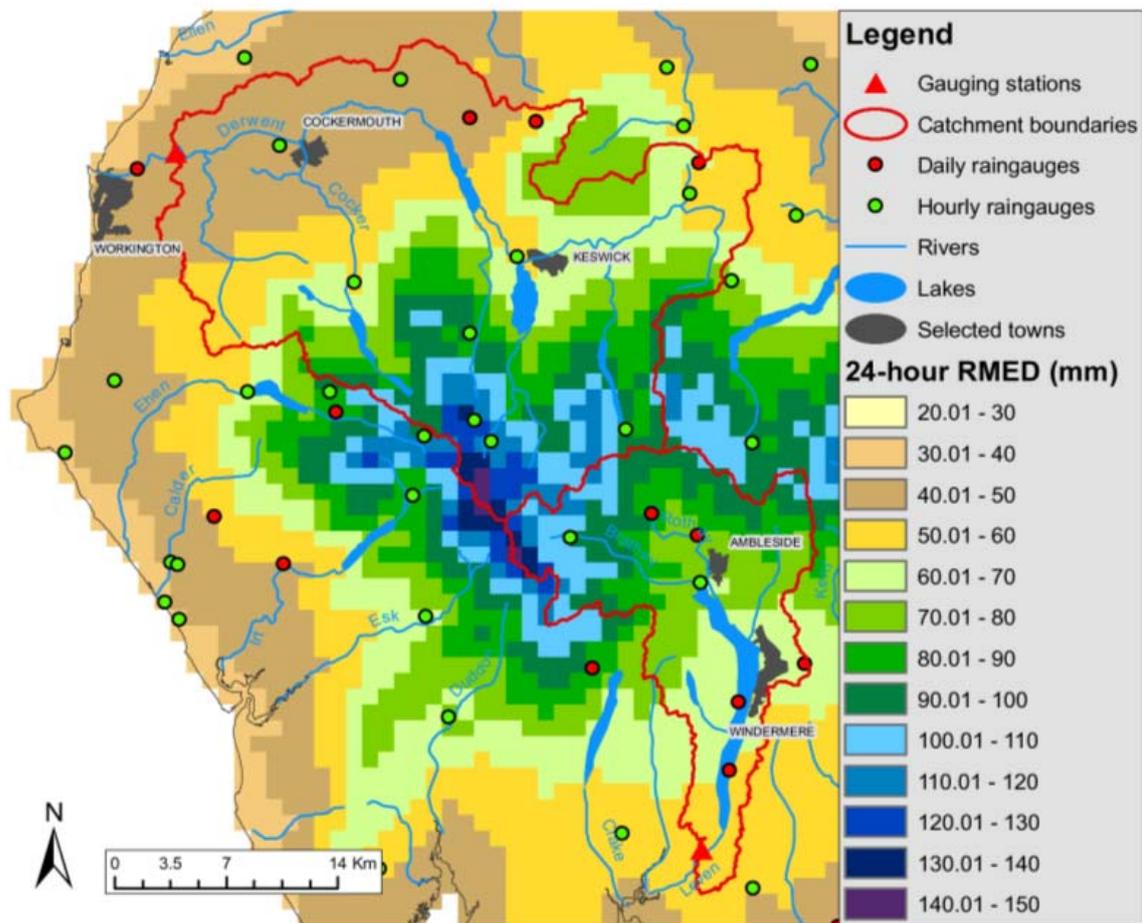


Figure 5 Variation of the median annual maximum 24-hour rainfall across the region using values from the $RMED_{24h}$ grid

Duration:	24 hour	24 hour
Season:	annual	annual
Data type:	FEH	# Res. Saf.
Focal point:	GB 3225 5135	GB 3225 5135
Radius (km):	200	# 200 (+100)
Netmax shift method:	geometric	# gam1_gam2
Segment fitting method:	revised (06/08)	# netmax (03/09)
Standardisation method:	FEH	# revised (06/08)
No. networks & segments:	5 6	--> 13 8 (+4 +2)
Rmed (mm) **:	85.6 f	--> 149.8 g (12)
SAAR (1961-90) (mm):	3389	3389

** rmed source at focal point: f = FEH DDF, g = gauged (no. of maxima in brackets), u = user-supplied

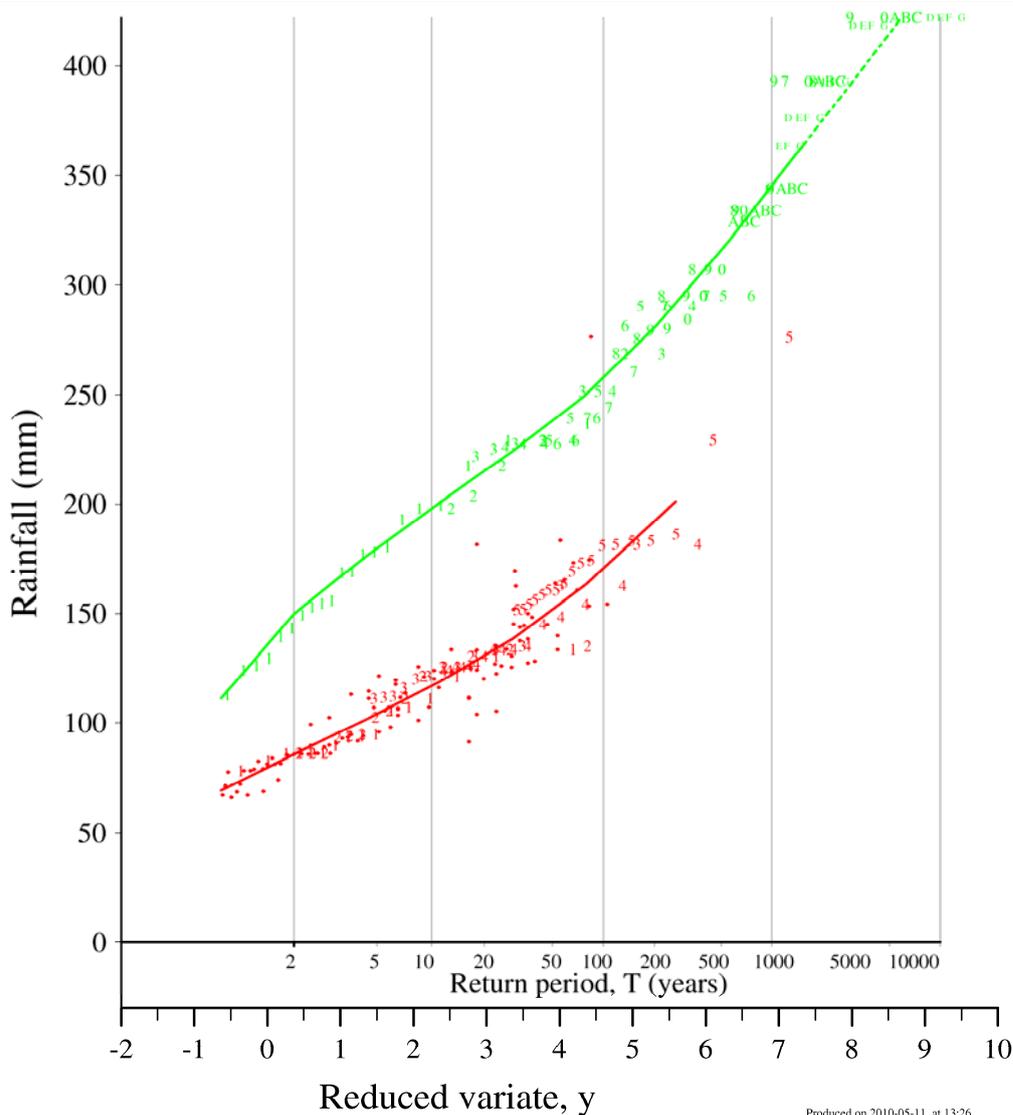


Figure 6 Comparison of the FEH FORGEX (red) and revised FORGEX methods (green) for the 24-hour duration focused on the Honister Pass raingauge site

Duration:	24 hour	24 hour
Season:	annual	annual
Data type:	FEH	# Res. Saf.
Focal point:	GB 3235 5121	GB 3235 5121
Radius (km):	200	# 200 (+100)
Netmax shift method:	geometric	# gam1_gam2
Segment fitting method:	revised (06/08)	# netmax (03/09)
Standardisation method:	FEH	# revised (06/08)
No. networks & segments:	5 6	--> 12 8 (+3 +2)
Rmed (mm) **:	113.1 f	--> 116.3 u
SAAR (1961-90) (mm):	3137	3137

** med source at focal point: f = FEH DDF, g = gauged (no. of maxima in brackets), u = user-supplied

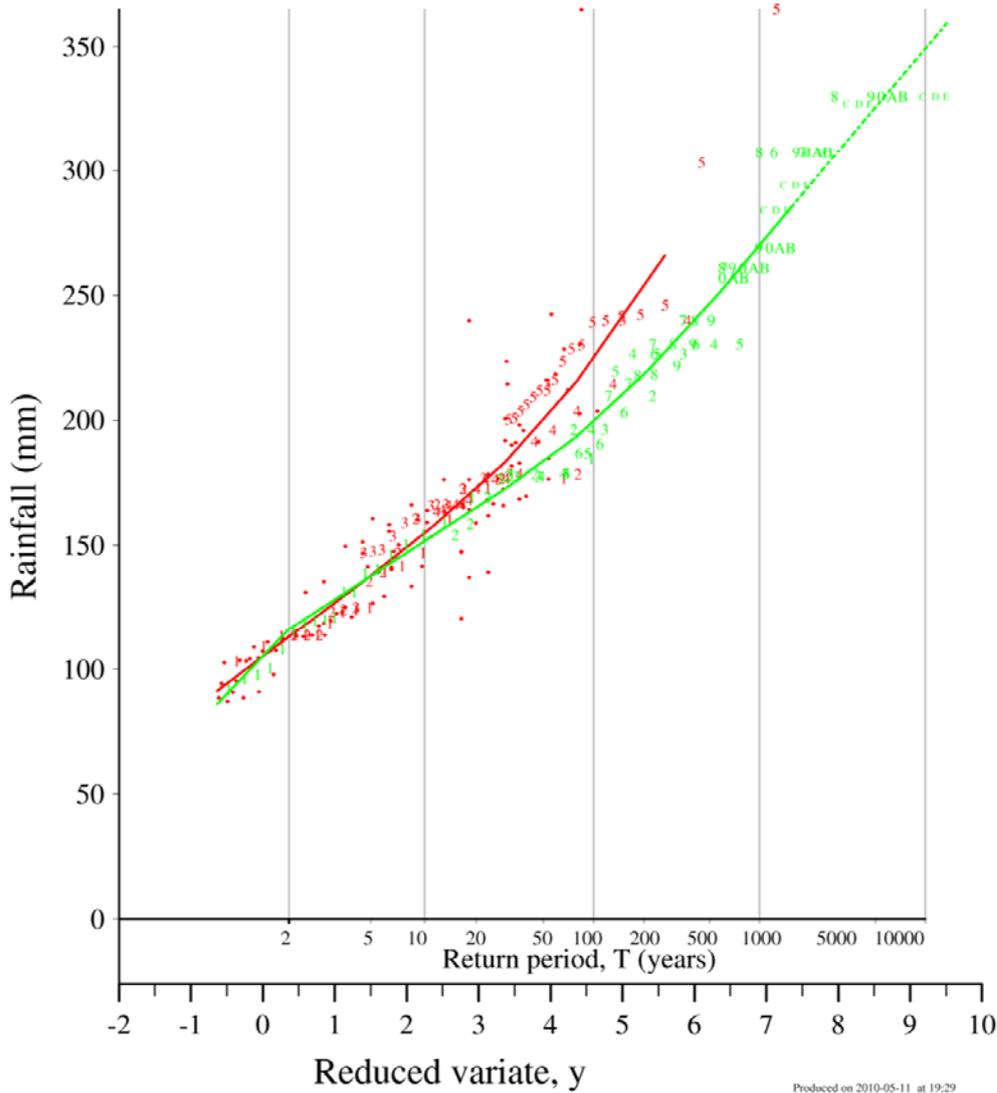


Figure 7 Comparison of the FEH FORGEX (red) and revised FORGEX methods (green) for the 24-hour duration focused on the Seathwaite Farm rain gauge site

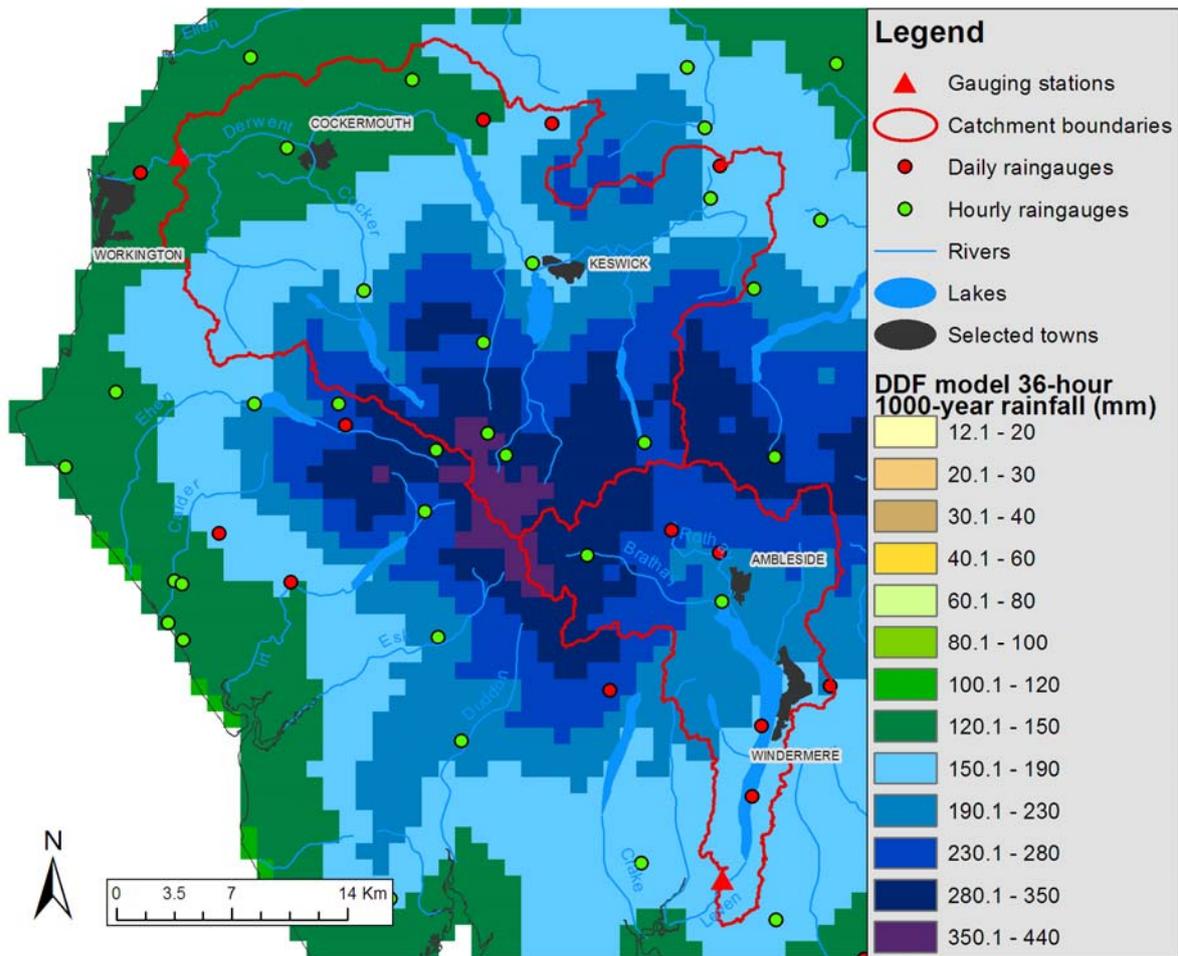


Figure 8 Results from the DDF model showing the estimated value of the annual maximum 36-hour rainfall with a return period of 1000 years for any point

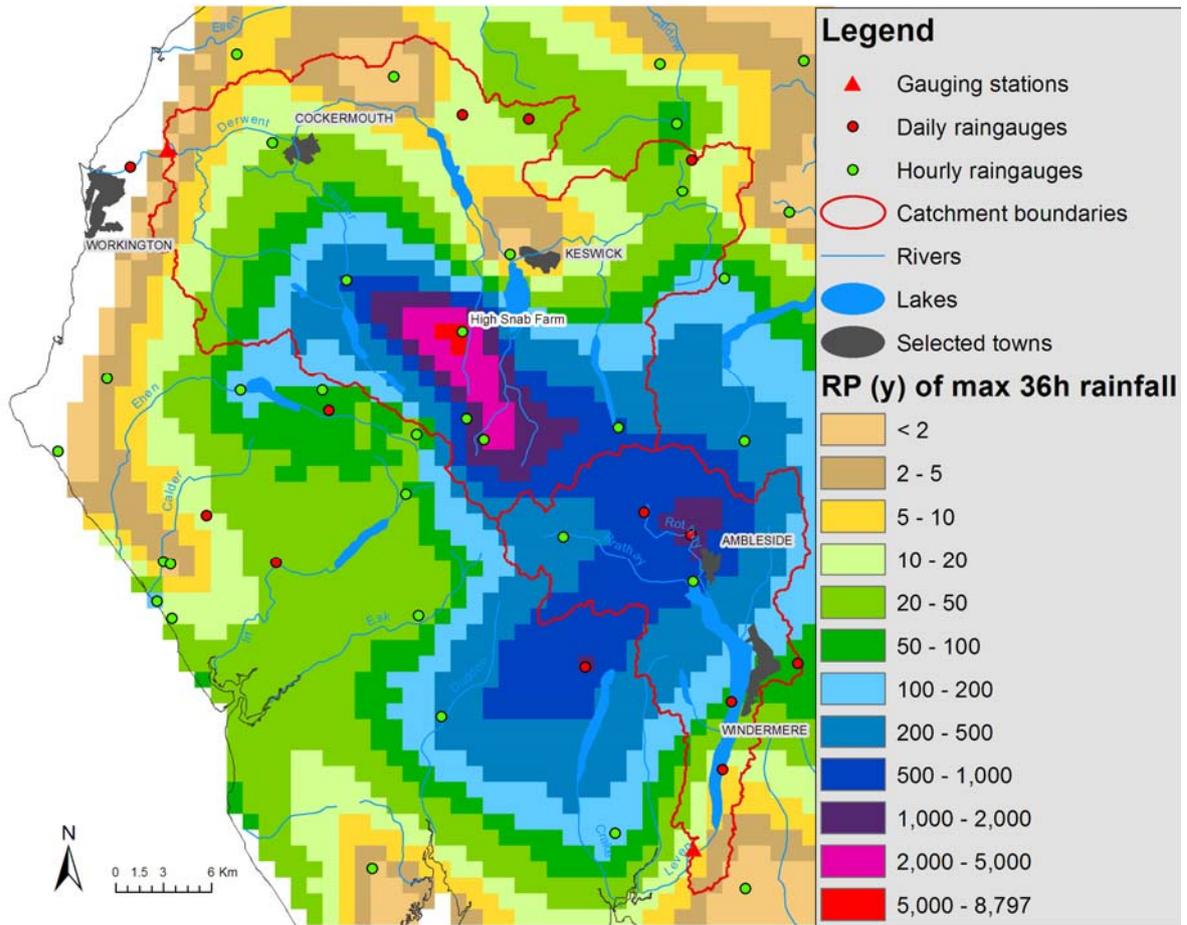


Figure 9 Estimated return period of the maximum 36-hour total rainfall experienced at each point in the region

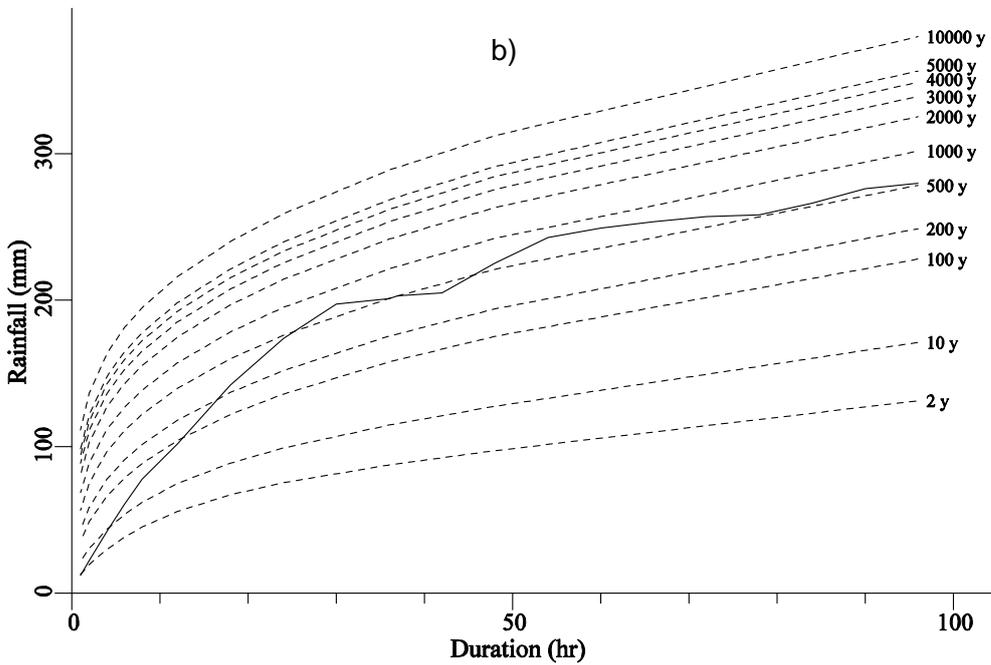
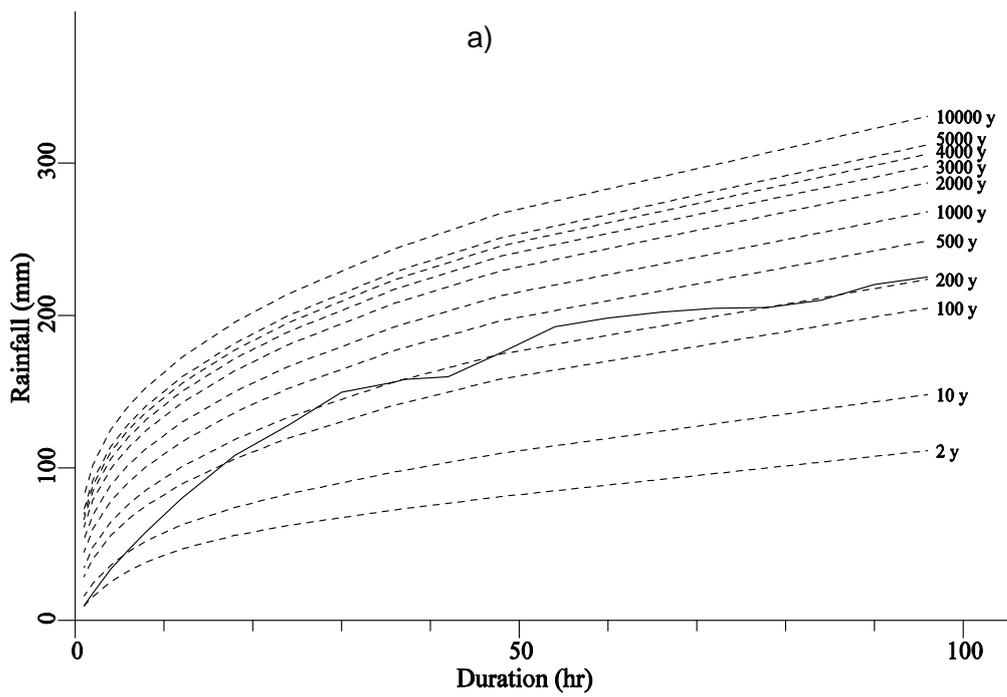


Figure 10 DDF curves of catchment average rainfall (dashed lines), together with the maximum catchment average rainfall of any duration for the event of November 2009, for a) the Derwent catchment and b) the Leven catchment