A hydrological assessment of the November 2009 floods in Cumbria, UK

J. D. Miller, T. R. Kjeldsen, J. Hannaford and D. G. Morris

ABSTRACT

In November 2009, record-breaking rainfall resulted in severe, damaging flooding in Cumbria, in the north-west of England. This paper presents an analysis of the river flows and lake levels experienced during the event. Comparison with previous maxima shows the exceptional nature of this event, with new maximum flows being established at 17 river flow gauging stations, particularly on catchments influenced by lakes. The return periods of the flood peaks are estimated using the latest Flood Estimation Handbook statistical procedures. Results demonstrate that the event has had a considerable impact on estimates of flood frequency and associated uncertainty. Analysis of lake levels suggests that their record high levels reduced their attenuating effect, significantly affecting the timing and magnitude of downstream peaks. The peak flow estimate of 700 $m^3 s^{-1}$ at Workington, the lowest station on the Derwent, was examined in the context of upstream inputs and was found to be plausible. The results of this study have important implications for the future development of flood frequency estimation methods for the UK. It is recommended that further research is undertaken on the role of abnormally elevated lake levels and that flood frequency estimation procedures in lake-influenced catchments are reviewed.

Key words | Cumbria, flood frequency, floods, lakes, November 2009, return period

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INTRODUCTION

On 19–20 November 2009, as a result of a prolonged period of record-breaking rainfall over the mountains of the central Lake District in north-west England, many of the rivers within the region experienced exceptionally high flows, with the greatest devastation occurring along the River Derwent and its tributaries. In parts of the southern headwaters of the Derwent, the rainfall averaged over 10 mm/hour for over 36 hours, and the raingauge at Seathwaite Farm in the headwaters of the Derwent recorded a new UK 24-hour maximum of 316.4 mm. The human consequences were greatest in the lower catchment, with around 200 people having to be rescued from the town of Cockermouth after nearly 900 properties were inundated, and with all road and footbridges over the Derwent in Workington being either destroyed or seriously damaged, in one case causing the death of a police officer.

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This paper presents a hydrological analysis of the event, paying particular attention to the part played by the numerous lakes in the region, most of which reached their highest level on record, and to the effect of the event on future assessments of flood rarity. It complements a companion paper (Stewart *et al.* 2011), which provides a statistical analysis of the event rainfall.

BACKGROUND

In the UK, a wet country (average annual rainfall of 1,126 mm; Met Office 2011) with a maritime climate, strongly influenced by the passage of moisture-laden westerly airflows, some form of significant fluvial flooding can be expected to occur in most years. In the recent past, however, flooding has been at the forefront of public attention and there is a widely held perception that flood risk is increasing. In part, this is due to a succession of major flood events, including nationally-significant, prolonged events with a wide spatial signature such as the floods of Easter 1998 (Horner & Walsh 2000), autumn 2000 (Marsh & Dale 2002) and summer 2007 (Marsh & Hannaford 2008) as well as more localised, short-lived, but dramatic and destructive events (e.g. the Boscastle floods of 2004; Doe 2004). These events have had a major impact on government policy, particularly given concern over the anticipated increase in flood severity in a warming world. The Pitt Review (Cabinet Office 2008), for example, commissioned after the 2007 floods, has had a major impact on flood management strategies in the UK. The vulnerability of society to flooding has also been brought to the fore by recent events: the summer 2007 floods were associated with 15 fatalities and an estimated cost of £3.2 billion (Chatterton *et al.* 2010). In Europe in the 20 years to 2008, economic losses due to flood disasters exceeded those from any other category of natural disaster (CRED 2009).

The intention of this paper is to add to a history of event-based contemporary flood studies in the UK (e.g. Acreman & Horrocks 1990; Black & Anderson 1993; Marsh & Dale 2002; Marsh & Hannaford 2008) and its findings should be viewed in the context set by studies that have systematically assessed a range of historical floods (e.g. Acreman 1989; Macdonald 2006). It is also hoped that this work may add to a growing international knowledge base of major flood events, as exemplified by the catalogue of maximum floods compiled by Herschy (2002), the archives of the Dartmouth Flood Observatory (www.dartmouth.edu/~floods/), and the many published examples of analyses of flood events in other countries; for example flooding in Poland in 1997 (Kundzewicz *et al.* 1999), China in the mid 1990s (Wang & Plate 2002) and the Elbe floods of 2002 (Ulbrich *et al.* 2003).

Analyses of extreme flood events are important for a number of reasons including the development of more effective flood-mitigation strategies, engineering design and reservoir safety, and, in particular, the significant influence of these events on return period analysis and consequently on planning and flood management decisions. Such events present an opportunity to test and refine flood estimation methodologies. In the UK, the statistical flood frequency procedures of the Flood Estimation Handbook (FEH) (Institute of Hydrology 1999) have recently been updated (Kjeldsen & Jones 2009), as has the FEH depth-duration-frequency (DDF) model for extreme rainfall frequency analysis (Stewart *et al.* 2010). The analysis of the November 2009 event is one of the first applications for these revised procedures.

DATA DESCRIPTION

Rainfall data were supplied by the North West Region of the Environment Agency, and comprised both daily totals and hourly totals for the period 16–25 November 2009 from all of the functioning raingauges: a total of 45 daily storage raingauges and 56 tipping bucket raingauges respectively. The gauge locations are shown in Figure 1.

Flow data at continuous 15 minute resolution for stations within Cumbria were supplied by the Environment Agency. Peak over threshold (POT) and annual maxima series (AMS) of peak flows for selected catchments (Table 1) were obtained from the Environment Agency's HiFlows-UK website (www.environment-agency.gov.uk/hiflows/search.aspx). Both were supplemented with more recent highest instantaneous flow data from the National River Flow Archive (NRFA).

All available digital lake level data for water bodies within Cumbria were supplied by the Environment Agency. These comprised daily mean and maximum levels available for the full period of digital record for 10 lakes (Table 2), and 15 minute levels for November 2009 for a subset of four lakes (Bassenthwaite Lake, Derwent Water, Ennerdale Water and Crummock Water). Longer records stored in charts exist, but for practical reasons were not included in this study.

ANTECEDENT CONDITIONS

Following the two very wet summers of 2007 and 2008, July and August 2009 were also exceptionally wet in north-west Britain. However, spring and early autumn were notably dry (Marsh *et al.* 2010) and throughout almost the entire country, sustained early autumn river flow recessions

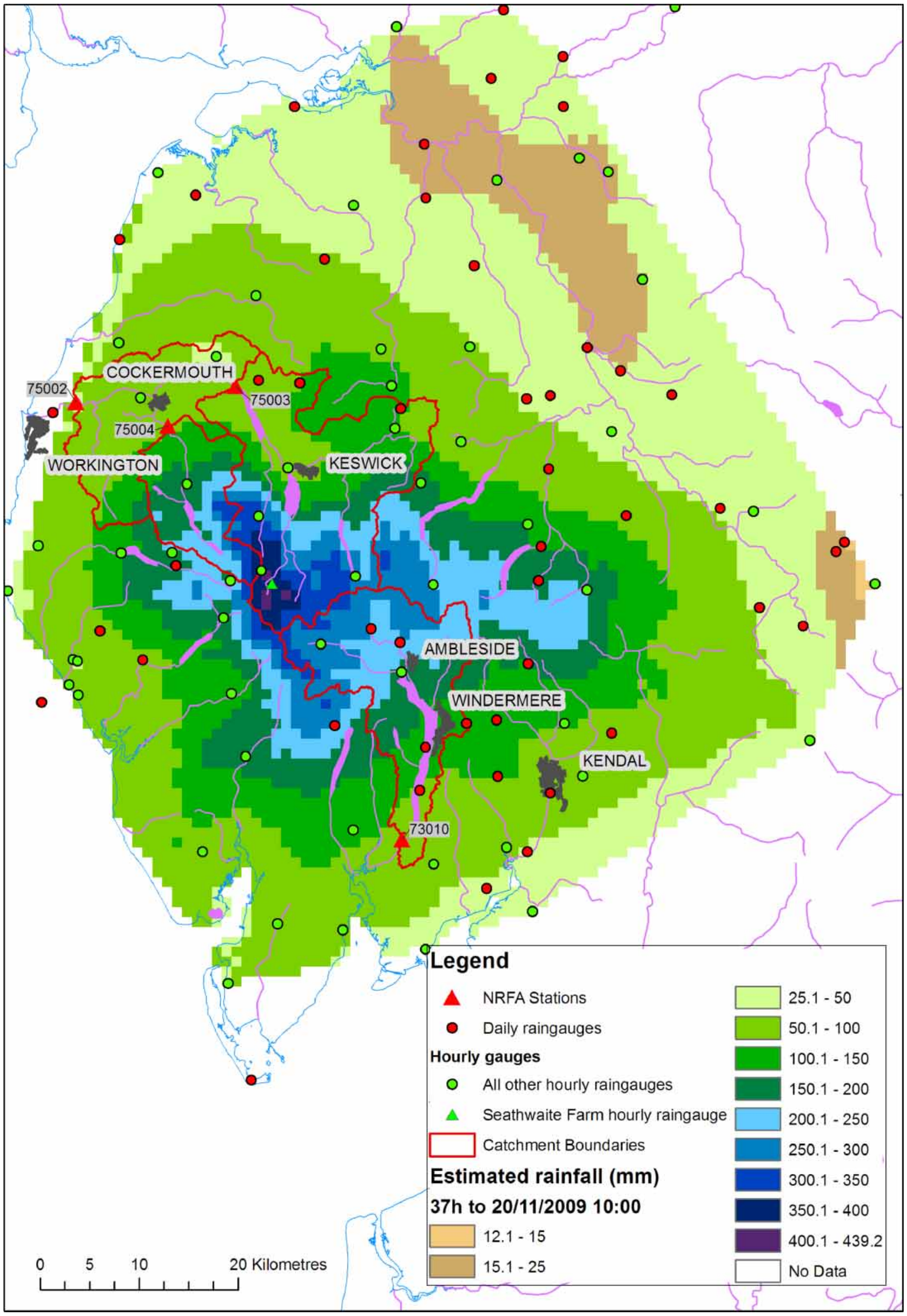

Figure 1 | Gridded 37 hour rainfall totals for the period ending 10:00 on 20/11/2009.

developed and continued into October, leaving river flows well below the seasonal average. In stark contrast, late autumn saw a continuous sequence of low pressure systems crossing the British Isles. The persistently cyclonic conditions resulted in rainfall on all but 2 or 3 days in November in most regions of the UK. As a result, catchments in much of the north and west of Britain were saturated and most rivers were in high spate early in the month (Marsh *et al.* 2010).

Table 1 | Catchments recording a new highest annual maximum (AMAX) value during the November 2009 event (catchments in Cumbria are in italics)

						Previous maximum		**November 2009**	
NRFA station	**Name**	**River**	**Period of record (years)**	**Area (km^2)**	**FARL**[a]	**Max flow m^3 s^{-1}**	**Date**	**Max flow m^{3}s^{-1}**	**Date**
73002	Low Nibthwaite	Crake	46	72.9	0.73	32.6	04/01/1982	50	20/11/2009
73006	Eel House Bridge	Cunsey Beck	36	18.77	0.727	14.3	04/01/1982	16.3	19/11/2009
73010	Newby Bridge FMS	Leven	64	247.81	0.694	135.3	02/12/1954	239	20/11/2009
73014	Jeffy Knotts	Brathay	38	56.59	0.907	90.5	10/01/2006	285	19/11/2009
74001	Duddon Hall	Duddon	41	86.01	0.985	200.7	03/08/1998	268	19/11/2009
74003	Bleach Green	Ehen	36	44.58	0.74	49.98	24/10/1977	102	20/11/2009
74008	Ulpha	Duddon	36	48.12	0.974	94.8	03/08/1998	104	19/11/2009
75001	Thirlmere Reservoir	St Johns Beck	35	41.88	0.721	102.7	08/01/2005	155	19/11/2009
75002	Camerton	Derwent	48	661.92	0.844	294	08/01/2005	700	19/11/2009
75003	Ouse Bridge	Derwent	41	363.01	0.789	196	08/01/2005	378	20/11/2009
75004	Southwaite Bridge	Cocker	42	116.17	0.83	86.7	08/01/2005	201	19/11/2009
75005	Portinscale	Derwent	38	237.26	0.846	163.9	08/01/2005	226	19/11/2009
75016[b]	Scalehill	Cocker	36	26.84	0.964	80	08/01/2005	192	20/11/2009
76001	Burnbanks	Haweswater Beck	31	32.34	0.645	51.8	14/12/2006	63.3	19/11/2009
76003	Udford	Eamont	48	407.17	0.86	399.4	08/01/2005	417	19/11/2009
76004	Eamont Bridge	Lowther	47	156.2	0.901	198.3	08/01/2005	200	19/11/2009
76015	Pooley Bridge	Eamont	33	149.24	0.743	108	08/01/2005	214	20/11/2009
78006	Woodfoot	Annan	25	217.95	0.995	176.7	21/09/1985	188	19/11/2009
80001	Dalbeattie	Urr	43	197.07	0.963	148.8	21/10/1998	150	19/11/2009
80002	Glenlochar	Dee	31	810.36	0.813	352.8	21/10/1998	391	20/11/2009
203010	Maydown Bridge	Blackwater	38	964.16	0.976	157	23/10/1987	187	20/11/2009

[a] Flood Attenuation by Reservoirs and Lakes index – the FEH index of how the median annual maximum flood will be attenuated (1 = no attenuation).

[b] Not in HiFlows-UK.

EVENT RAINFALL

Between the 18th and 20th November 2009, a warm, moist south-westerly airstream affected the UK and 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, together with substantial orographic enhancement, produced many gauged rainfall totals in excess of 50 mm and culminated in rainfall depths of over 350 mm in 36 hours across high ground in the central Lake District. A new UK record was established at the Seathwaite Farm raingauge, Borrowdale, with 316.4 mm over the 24-hour period ending at 00:00 on the 20th November. Stewart *et al.* (2011), using the revised DDF model, estimated that this has a return period of 1,862 years, in contrast to the value given by the original FEH DDF model of 158 years. It should be noted that the Seathwaite Farm 24-hour total also exceeds the previous UK maximum for any two consecutive rainfall days (315 mm, also at

Table 2 | Lake level details for lakes with available digital daily maximum level records within Cumbria

	Record start date	Record end date	Previous maximum level (mAOD)	Date of previous maximum	November 2009 maximum level (mAOD)
Bassenthwaite Lake	15–06–1999	16–02–2010	71.29	08–01–2005	72.56
Coniston Water	03–03–1969	23–02–2010	45.27	26–10–2008	45.99
Crummock Water	31–10–1973	16–02–2010	99.49	23–10–2008	99.82
Derwent Water	19–07–1995	16–02–2010	77.30	08–01–2005	77.86
Ennerdale Water	01–12–1973	23–02–2010	113.51	04–01–1982	113.63
Haweswater	23–04–1997	23–02–2010	241.46	14–12–2006	241.54
Thirlmere	29–10–1997	16–02–2010	179.95	07–01–2005	180.11
Ullswater	01–11–1961	25–02–2010	147.01	08–01–2005	147.70
Wast Water	01–05–1979	23–02–2010	62.66	26–10–2008	62.96
Windermere	29–02–1968	23–02–2010	41.19	26–10–2008	41.91

Seathwaite Farm, on 4–5 December 1864) (Eden & Burt 2010). The previous 24 hour record was 279 mm, recorded at a daily (0900–0900) raingauge during the Martinstown, Dorset, storm of July 1955; this remains the rainfall-day maximum.

Analysis of the hourly Seathwaite Farm record (Stewart *et al.* 2011) showed the accumulation with the highest return period (estimated at 4,202 years) was the 401.6 mm falling in the 37 hour period ending at 10:00 on the 20th November. The spatial distribution of the rainfall over this period is shown in Figure 1; this was derived by Stewart *et al.* (2011) by interpolating raingauge observations on a 1 km square grid at an hourly time step.

The distribution in time of the catchment average hourly rainfall (CAHR) over the Derwent catchment and two subcatchments is included in a figure later in the paper (Figure 11).

RIVER FLOWS

Table 1 lists the 22 UK river flow gauging stations at which a new maximum was recorded in the November 2009 event; the majority, 17, of these are in Cumbria (in italics). Figure 2 maps flow gauging sites with reliable high-flow data in Cumbria and parts of south-west Scotland and north Lancashire, showing their November 2009 peak flow as a percentage of their previous highest flow. Comparison of Figures 1 and 2 shows the relationship between the area of most intense rainfall and the location of the new river flow records. The degree to which the former records have been surpassed is remarkable when it is considered that most of these stations have long records; with an average of 41 years and a maximum of 66 years at Newby Bridge (73010) (downstream of Windermere, where the November 2009 peak was 177% of the previous). The period of record includes a number of major floods, in particular January 1982 and December 1954 in the south of the region, and January 2005 and October 2008 in the west.

It is important to be aware that many of the November 2009 flows in Table 1 are the best available estimates based on extrapolation of station ratings from hydraulic models, as most of the rivers were out of bank and above the maximum gauged stage (Peter Spencer, Environment Agency, personal communication, 2010). The gauging station on the Derwent at Camerton (75002) was badly damaged during the event (Everard 2010) and was subsequently demolished.

Anecdotal evidence of extreme flood events within the region dating back several centuries is available (Black & Law 2004), though usually this is not associated with a quantitative assessment of the flood magnitude. While such information can potentially be brought into a site specific flood frequency analysis (e.g. Bayliss & Reed 2001), there is currently no formal, widely-agreed

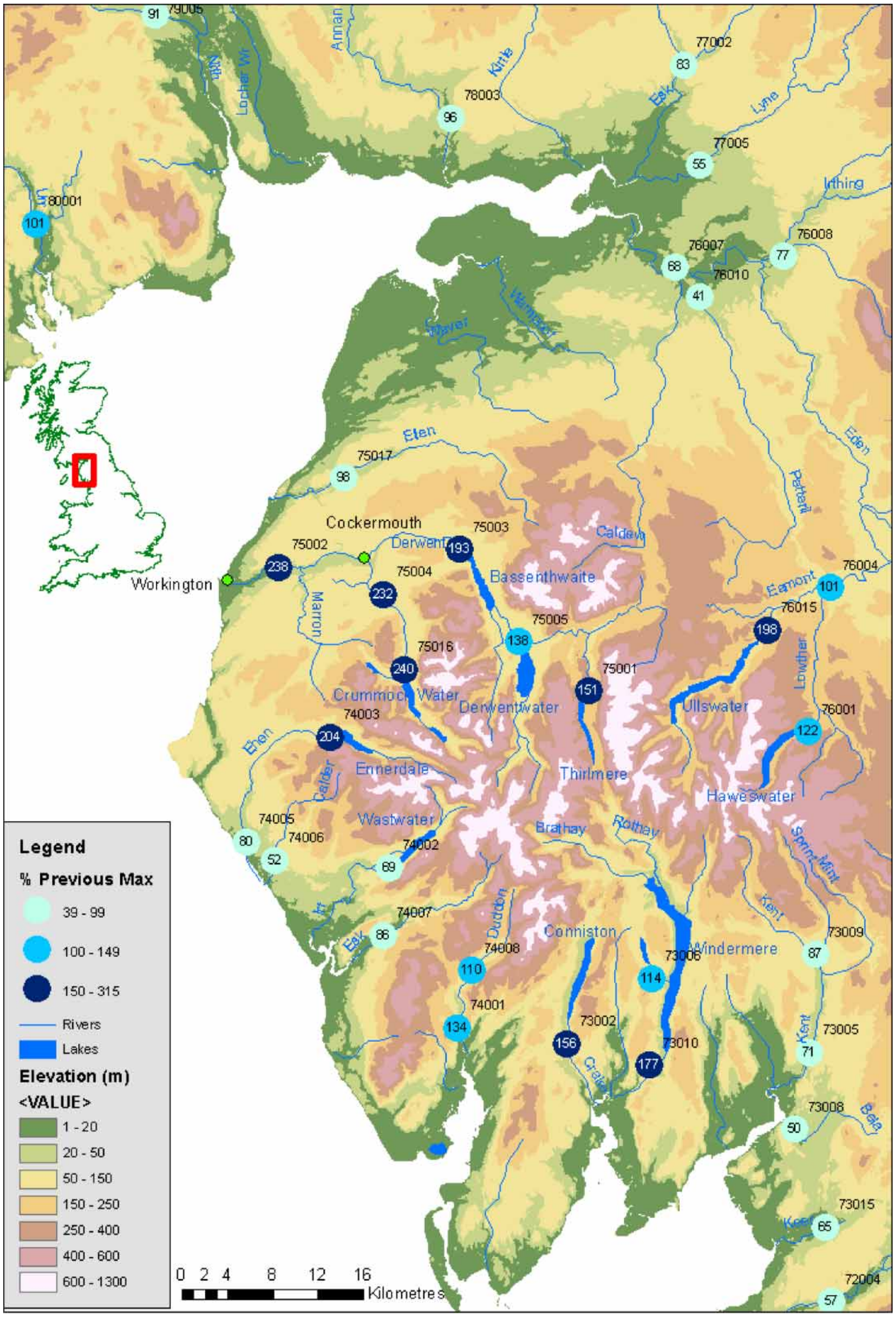

Figure 2 | Peak flows during the November 2009 flood event; expressed as a percentage of the previous maxima.

procedure for incorporating information from historical flood events into the statistical modelling framework underpinning the FEH procedures. It was therefore not deemed feasible to incorporate anecdotal evidence in the present study, which attempts to use the event to test standard FEH techniques.

STATISTICAL ANALYSIS OF RIVER FLOWS

The return period of the November 2009 flood was assessed by conducting a flood frequency analysis using both single-site and pooling group methods as described in the recent update to the FEH methodology (Kjeldsen & Jones 2009). The single-site analysis consists of fitting a suitable statistical distribution to the observed AMS of peak flow available at each site. Given the large degree of uncertainty generally associated with extrapolation of flood frequency curves fitted using at-site data only, it is common practice to use regional frequency analysis, which combines (into a pooling group) the at-site data with flood data from other gauged catchments considered hydrologically similar to the site of interest. The statistical distribution is then fitted as a weighted average to all the flood data in the pooling group. This procedure is typically referred to as a 'pooled analysis' but in the case where flood data are available at the site of interest, the weight within the pooling group of the at-site data is increased significantly and a more appropriate name is 'enhanced single site analysis' (Kjeldsen & Jones 2009). The advantage of introducing data from other sites into the analysis is generally considered to be a reduction in the prediction uncertainty when extrapolating the flood frequency curve to higher return periods. This reduction in uncertainty is, however, balanced against the risk of introducing data that does not fulfil the underlying assumptions of the data transfer, thereby introducing an element of model error.

Both the single-site and the pooled (or enhanced single-site) analysis have been performed on two datasets: one containing the annual maxima series from the HiFlows-UK version 3.02 database up to the end of water year 2007, and the other using an updated version in which the records for selected Lake District stations have been extended to include annual maximum data for water-year 2008 and the peaks for November 2009, treating it as if it were the annual maximum for water year 2009. This enables the effect of this major event on assessments of flood frequency to be demonstrated. Flood frequency analysis was not carried out for those stations known to have poor quality data, i.e. those classified as unsuitable for QMED (median annual maximum flood) estimation (76014 and 75001) or which are not included on the HiFlows database at all (75016). Also, data from station 76001 were excluded from the frequency analysis due to the heavily impacted flow regime resulting from operation of the upstream Haweswater reservoir.

Procedure

For both the single-site and the pooled analysis, the analysis uses the three-parameter Generalised Logistic (GLO) distribution as recommended for flood frequency analysis in the UK by Kjeldsen *et al.* (2008). For a GLO distribution, the relationship between the return period T, expressed in years, and the corresponding peak flow value Q_T is defined using the inverse of the cumulative distribution function (cdf) as:

$$Q_T = \xi + \frac{\alpha}{\kappa}(1 - (T-1)^{-\kappa}) = \xi\left[1 + \frac{\beta}{\kappa}(1 - (T-1)^{-\kappa})\right] = \xi z_T \tag{1}$$

where ξ, α, $\beta = \alpha/\xi$, and κ are GLO model parameters, and z_T is the value of the growth curve at return period T defined by the term within the square brackets in Equation (1). The GLO model parameters are estimated using a variant of the method of L-moments (Institute of Hydrology 1999). The location parameter ξ is defined as the median annual maximum flood, and the two parameters controlling the growth curve (β and κ) are estimated using higher order L-moment ratios (L-CV and L-SKEW). For the single-site analysis, estimates of L-CV and L-SKEW are obtained directly from the AMS. For the pooled analysis, estimates of L-CV and L-SKEW are weighted averages of L-moment ratios from a collection of sites (a pooling group) considered to be hydrologically similar to the site of interest in terms of their catchment characteristics: catchment area, annual average rainfall for the period 1961–1990, an index of attenuation of the median annual flood peak due to upstream reservoirs and lakes (FARL) (Bayliss 1999) ($1 =$ no attenuation; attenuation increases with decreasing FARL), and an indicator of the spatial extent of the 100-year flood plain as derived from the indicative UK flood maps developed by Morris & Flavin (1996). A more detailed description of the pooling group method is provided by Kjeldsen & Jones (2009).

For catchments in Table 1 with a suitable AMS, the return period of the November 2009 flood event was obtained from Equation (1).

In addition to the return period, the uncertainty of the return period estimate was obtained by a simple graphical assessment based on approximate confidence intervals for the flood frequency curve. For a set of defined return periods ranging from 1.01 to 50,000, the approximate standard deviation of the design flood, Q_T, was estimated using the methods described by Kjeldsen & Jones (2004, 2006) for assessing the sampling variance of design flood events when using the GLO distribution with the FEH statistical method. For the pooled analysis, the variance estimator by Kjeldsen & Jones (2006) was updated to be consistent with the improved pooling group method. For both the single-site and the pooled analysis, the estimates of the confidence intervals of the design flood events were originally developed assuming the design flood to be normally distributed. However, given the relatively large return periods under consideration in this study, it was considered to be more appropriate to adopt an assumption that the design floods follow a log-normal distribution, in which case the $100(1-\alpha)\%$ confidence interval for the design flood, Q_T, *is* given as:

$$\left[\exp\left(\ln(Q_T) - z_{1-\alpha/2}\sqrt{\frac{\mathrm{var}\{Q_T\}}{Q_T}}\right);\right.$$
$$\left.\exp\left(\ln(Q_T) + z_{1-\alpha/2}\frac{\sqrt{\mathrm{var}\{Q_T\}}}{Q_T}\right)\right]$$

The confidence interval for an estimate of return period for a given peak flow value was obtained subsequently by graphically interpolating horizontally the return period associated with the upper and lower confidence limits for a given point on the flood frequency curve (Figure 3). If the upper limit of the confidence of the return period exceeds 50,000 years, the upper limit is given as ‘ >50,000 years’.

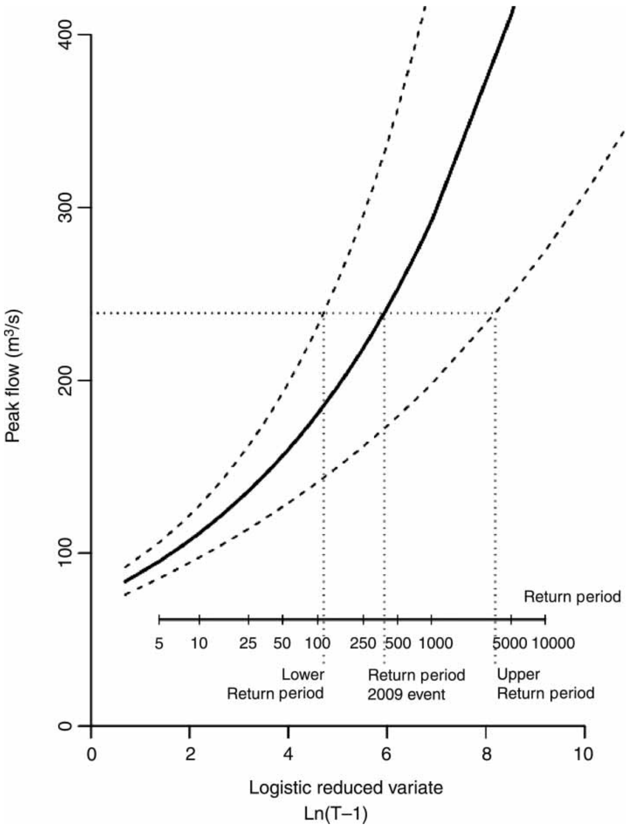

Figure 3 | Flood frequency curve showing return period estimation and associated uncertainty.

Results from the single-site analysis

Table 3 presents the results of applying the single-site method to the two datasets. The length of the upper confidence interval emphasises the level of uncertainty associated with the use of single site analysis. This is problematic for assessment of floods with a return period well in excess of the record length. The large reduction in the estimated return period of the event resulting from the inclusion of the event in the fitting of the flood frequency curve is an indication of the influence of this very large event on the fitted curve.

Results from pooled catchment analysis

The results from the pooling group method are given in Table 4. Less uncertainty in the return period assessments compared with the single-site analysis is evident in all catchments. Estimated return periods are shortened, often greatly, when incorporating the 2009 event. This is because the 2009 event will in many cases have affected several of the pooled gauges, in particular the at-site gauge, which, as stated

Table 3 | Single-site return period assessment

			Using data to 2008			**Incorporating the 2009 event**		
NRFA Ref number	**No. ann. max**	**November 2009 peak flow (m^3/s)**	**Return period (years)**	**95% confidence interval–lower and upper limit (years)**		**Return period (years)**	**95% confidence interval–lower and upper limit (years)**	
73002	45	50	900	113	>50,000	164	39	>50,000
73006	36	16.3	114	27	>50,000	57	17	>50,000
73010	65	239	964	143	>50,000	232	52	>50,000
74001	42	268	456	69	>50,000	118	28	>50,000
74003	37	102	20,485	412	>50,000	213	37	>50,000
74008	37	104	58	18	>50,000	39	14	>50,000
75002	49	700	>50,000	33,506	>50,000	771	100	>50,000
75003	42	378	>50,000	1,134	>50,000	311	50	>50,000
75004	43	201	3,570	271	>50,000	213	38	>50,000
75005	37	226	21,509	322	>50,000	228	40	>50,000
76003	48	417	109	32	>50,000	62	20	>50,000
76004	47	200	30	13	1,518	27	12	819
76015	33	214	>50,000	12,767	>50,000	280	39	>50,000

Table 4 | Pooled (enhanced single-site analysis) return period assessment

			Using data to 2008			**Incorporating the 2009 event**		
NRFA Ref number	**No. ann. max**	**November 2009 peak flow (m^3/s)**	**Return period (years)**	**95% confidence interval–lower and upper limit (years)**		**Return period (years)**	**95% confidence interval–lower and upper limit (years)**	
73002	45	50	477	143	3,888	167	62	806
73006	36	16.3	67	28	256	46	20	153
73010	65	239	1,931	409	43,823	383	112	3,609
74001	42	268	539	158	4,676	278	81	2,479
74003	37	102	1,799	402	28,712	353	94	3,661
74008	37	104	45	22	105	39	19	93
75002	49	700	>50,000	9,215	>50,000	2,102	507	17,706
75003	42	378	40,911	4,959	>50,000	1,386	315	18,400
75004	43	201	3,594	766	>50,000	769	163	13,591
75005	37	226	348	111	2,586	111	44	467
76003	48	417	192	73	756	88	38	264
76004	47	200	30	15	84	26	13	70
76015	33	214	5,877	1,066	>50,000	460	122	4,289

above, is now given enhanced weight. This is illustrated in Figure 4 for station 75002, Derwent at Camerton, showing how the estimated return period has been shortened from 104,181 years to 2,102 years. Figure 4 also shows the annual maxima for the station, each plotted at its most probable return period based on its rank and the number of

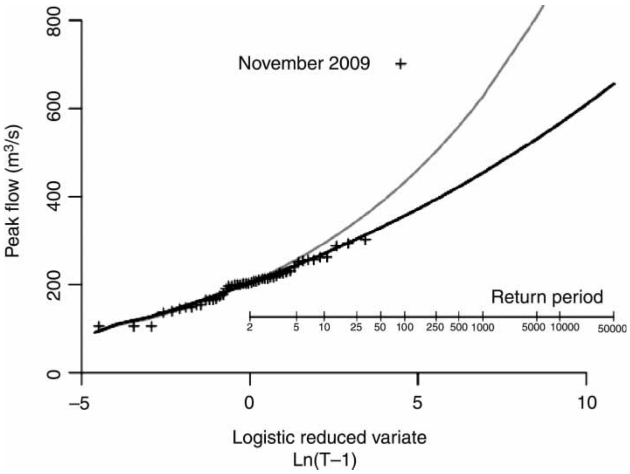

Figure 4 | Flood frequency curves (pooled method) for the River Derwent at Camerton (75002) prior to the November 2009 event (black) and including the event (grey).

maxima, according to the commonly used Gringorten formula (Gringorten 1963); note there is considerable uncertainty in such return periods for the highest ranked maximum.

EFFECT OF LAKE HYDROLOGY ON THE NOVEMBER 2009 EVENT

Flood attenuation

The hydrological response of much of the Lake District is dominated by its lake systems. The effect of these lakes on downstream flows is to attenuate the incoming rapid runoff from the impermeable rock and frequently saturated thin soils, slowing the flood response downstream and smoothing out flashy flows.

During the event occurring between the 18th and 20th November 2009, inflows to the lakes caused a rapid rise in levels, with levels in Derwent Water and Bassenthwaite Lake rising respectively to nearly 0.6 and 1.2 m higher than previously recorded at the Environment Agency's stations. As a result, significant flow occurred over the floodplain downstream of Derwent Water towards Bassenthwaite Lake, with the two water bodies appearing to be as one. This has been noted on nine previous occasions since 1831 (Spencer 2011; Report to EA 2010), though since the 1970s the combined water body has been split by the embanked A66 road, under which the water flows through the Derwent bridge and 10 flood relief arches.

Lake levels in all the major lakes within the region reached new recorded maxima during the November 2009 flood event and in many cases exceeded previous records on the Environment Agency's digital record by a large margin (Table 2). Furthermore, river flow data from the gauging stations immediately downstream of Bassenthwaite Lake and Windermere imply that, at these lakes, the November 2009 levels were not exceeded during the period commencing 1968 and 1939, respectively.

With lake levels so high and the consequent possibility of discharge across a broader length of shoreline than their normal river outlet (topographic surveys would be required to quantify this), their buffering effect on the passage of flood flows is likely to have been reduced. Figure 5, which compares the Bassenthwaite Lake inflows and outflows for this event, and for the next largest on record, January 2005, would appear to support this theory. Because all of the inflows to the lake have not been gauged (catchment areas are 363 km^2 at the outflow station (75003) Ouse Bridge, and 235 km^2 at the upstream station (75005) Portinscale) the flows have been scaled by catchment area, so that the resultant Portinscale hydrograph can be considered to be an approximation of all the inputs to the lake. In 2005, there is considerable reduction and delay to the flood peak, but in 2009 the lake appears to have much less effect on timing and no effect on magnitude. The fact that in 2009 the scaled outflow peak exceeds the inflow is likely to be due to uncertainties in the extrapolation of rating curves at Portinscale and the relative size of the flood that entered the lake from Newlands Beck – the tributary shown entering the southern corner of the lake in Figure 2.

Independent analyses of the November 2009 event within the Derwent catchment lake systems, using a 1D hydrodynamic model, arrive at a similar conclusion whereby large floods may pass through the system with less attenuation (Spencer 2010).

Relationship between lake levels and discharge

Figures 6 and 7 illustrate the relationship between peak outflows and lake levels for, respectively, Bassenthwaite

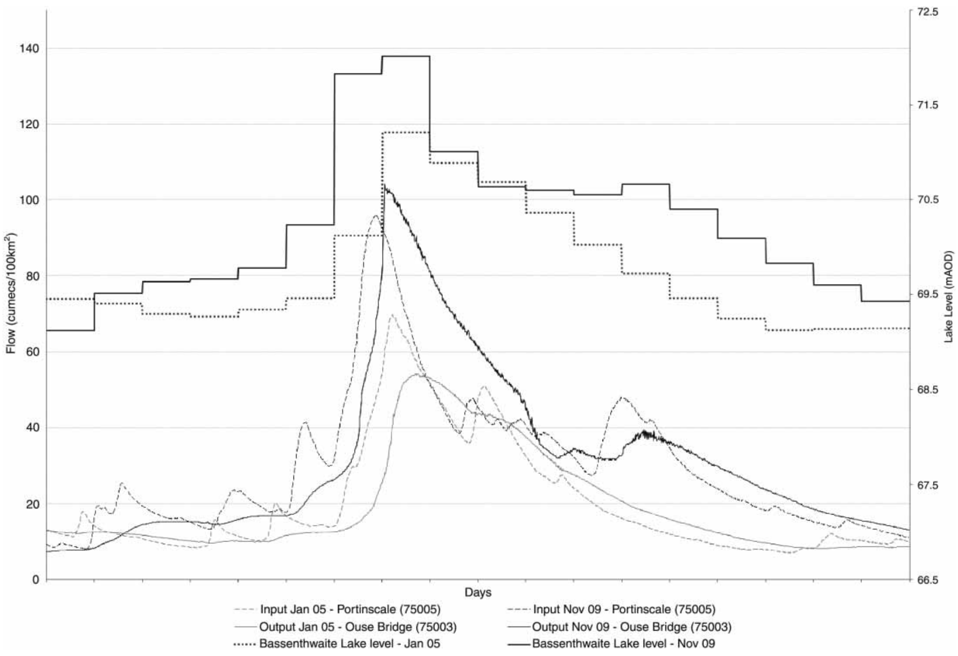

Figure 5 | Upstream (Portinscale) and downstream (Ouse Bridge) scaled hydrographs with mean daily lake level in Bassenthwaite Lake for the November 2009 event and the previous record of January 2005.

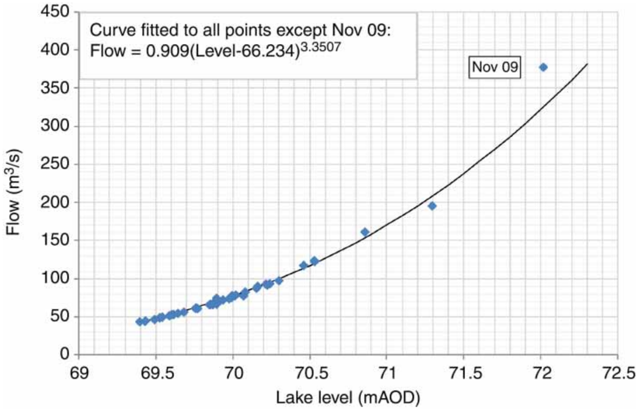

Figure 6 | Bassenthwaite Lake maximum daily lake level plotted against POT event flows at Ouse Bridge gauging station (75003).

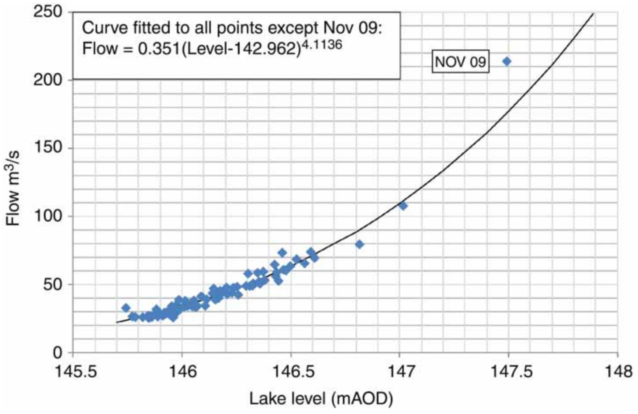

Figure 7 | Ullswater maximum daily lake level plotted against POT event flows at Pooley Bridge gauging station (76015).

Lake and Ullswater. The flood peaks are from the HiFlows-UK peaks over threshold (POT) dataset for the gauging stations immediately downstream of the lakes (75003 Derwent at Ouse Bridge, and 76015 Eamont at Pooley Bridge, respectively). The lake levels are the daily maximum on the day of the flood peak. The lines represent standard rating curves fitted to all data points except November 2009. Both plots reveal the relative magnitude of lake level and outflow of the November 2009 event compared with previous events. In both cases the peak flow observed is clearly in excess of the projected rating curve flow for the coincidental lake level. This could indicate that at such high lake levels a different stage discharge relationship applied at both outlets.

Comparison of flood hydrographs for lake and non-lake catchments

A comparison of hydrographs for catchments within the region reveals the differences in hydrological response to extreme events. Figure 8 displays the event hydrographs for the peak over threshold floods experienced during the period 2003–2009 at three lake-influenced catchments (73010 (downstream of Windermere), 75003 (downstream of Bassenthwaite and Derwent Water) and 76015 (downstream of Ullswater)) and three without lake influences (74001, 74007 and 75017). For each station, the individual event hydrographs are plotted with the time of their peaks aligned. Also shown is the mean of the event hydrographs, and the November 2009 event with its time of peak aligned with the other events. The individual events show the clear

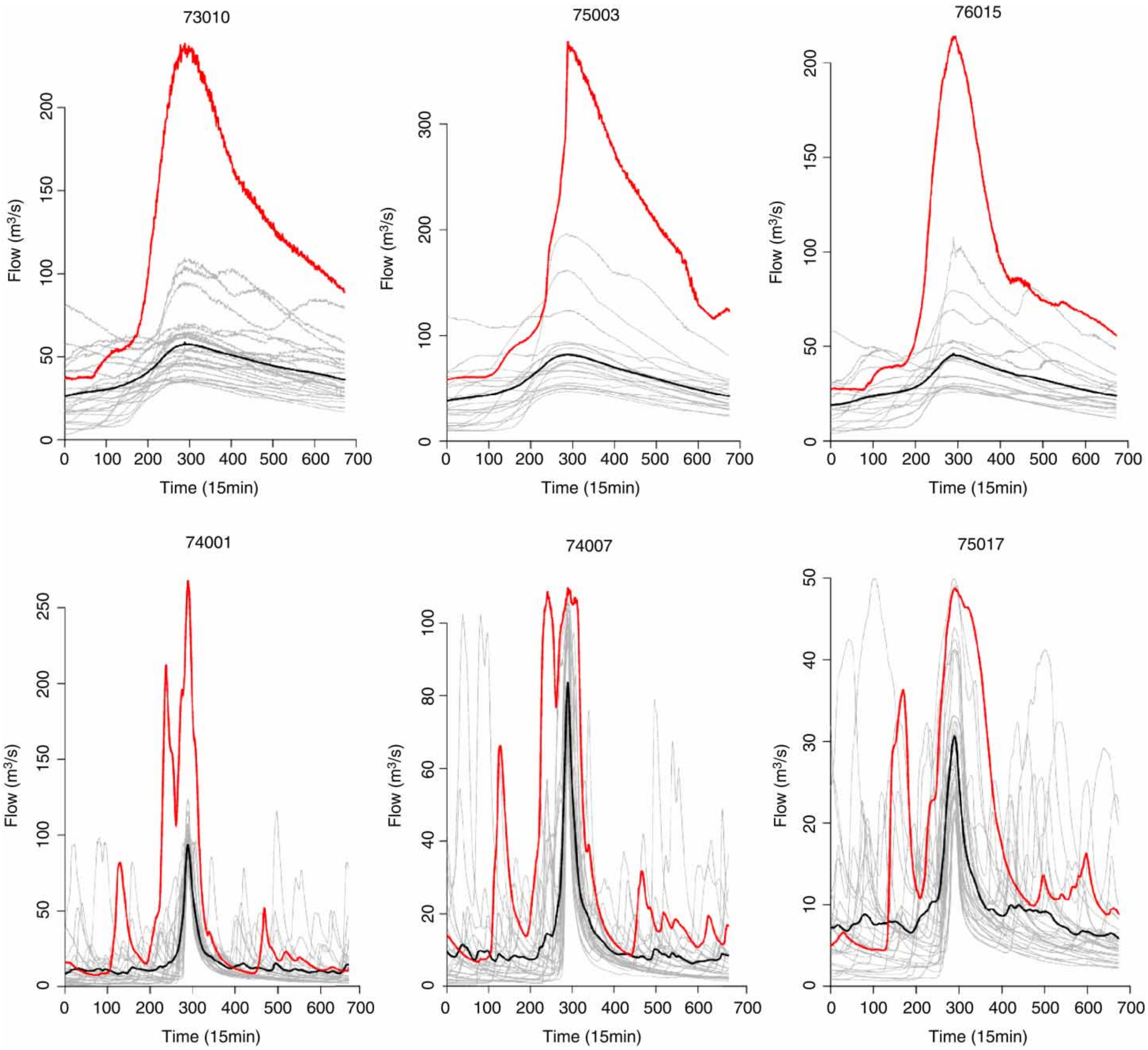

Figure 8 | POT hydrographs for period 2003–2009 for lake-influenced catchments (above) and non-lake-influenced catchments (below), with the mean flood hydrograph denoted by the dark black line and the November 2009 event as a dotted line. The units on the *x*-axis represent number of 15 min time steps.

difference in flood response between the two sets of catchments, with the lake-influenced catchments being less flashy and having less variation between events. However, the 2009 event does not fit this pattern. On the three lake-influenced catchments it is an extreme outlier in magnitude compared with the mean, and its profile is more akin to that expected from a non-lake catchment. It appears that the usual damping effect of the lakes is much diminished. To a degree, this comparison is influenced by the position of the catchments relative to the area of most extreme rainfall, but Figures 1 and 2 show that 74001 and 74007 received a similar amount of rainfall to 76015.

PLAUSIBILITY OF THE PEAK FLOW ESTIMATE NEAR WORKINGTON

The flow value of greatest interest in the November 2009 event is the peak on the Derwent at Workington. Flows here are measured 5 km upstream of Workington at the Camerton gauging station (75002), which, as stated earlier, was destroyed during the event. Bankfull capacity at the station is estimated at 400 $m^3 s^{-1}$ (Marsh & Hannaford 2008) and peak flow estimates were derived by the EA from 1D ISIS river modelling and nearby station estimates. The purpose of this section is to assess the plausibility of the 700 $m^3 s^{-1}$ estimate for the flood peak at Camerton in the light of the points raised in this paper.

The extraordinary flows along the Derwent that caused widespread damage to Cockermouth and Workington were of a magnitude expected to be exceeded, on average, once every 2,102 years according to pooled return period assessments including the event (Table 4). As shown by the plot of the POT hydrographs recorded at Camerton in Figure 9, the event hydrograph is altogether different in magnitude and shape to previous events and the mean hydrograph.

The relative difference in hydrological response between the two main catchments feeding into the Derwent at Cockermouth and ultimately Workington is illustrated in Figure 10. Crummock Water (in the Cocker catchment) levels rise less markedly and peak earlier (20:00–22:00, 19/11/09) than those in Bassenthwaite Lake (00:00–02:00, 20/11/09), and the resulting downstream hydrograph from

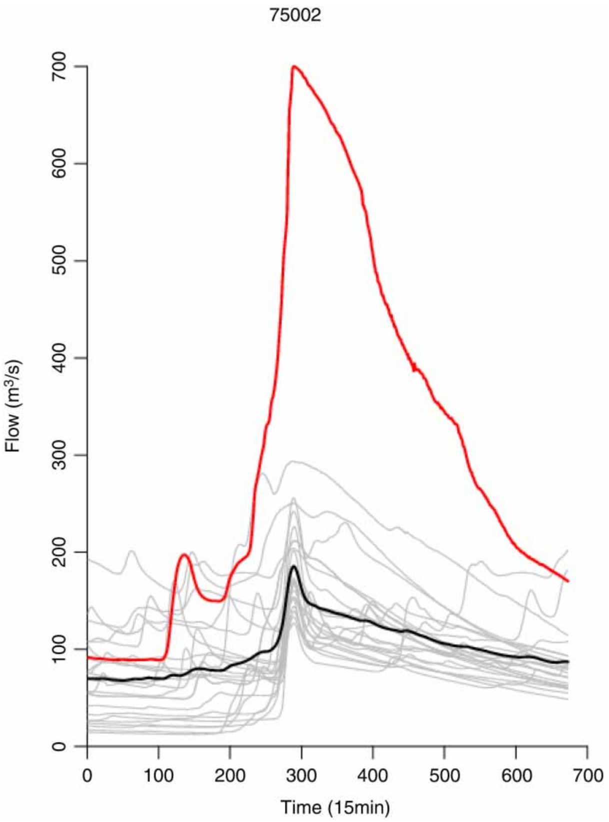

Figure 9 | POT hydrograph plot for the period 2003–2009 for Camerton station at Workington (75002), showing mean hydrograph in black and the November 2009 event as a dotted line. The units on the *x*-axis represent number of 15 min time steps.

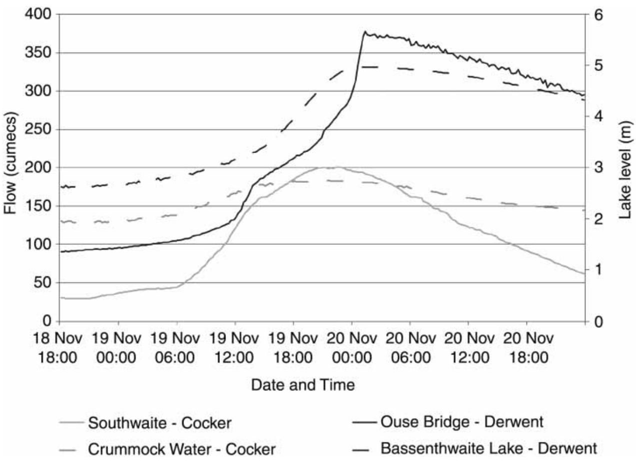

Figure 10 | Station hydrographs and lake levels within the Derwent and Cocker catchments over the period 18:00 18/11/2009 to 02:00 21/11/2009.

stations on the Cocker show more attenuation. Peak flows within the Cocker catchment at Southwaite Bridge are around 3 hours earlier than those at Ouse Bridge in the Derwent catchment. This reflects the increased travel time of runoff within the Derwent catchment, but differences in the timing of peaks would normally be more pronounced due to the attenuating effects of both Derwent Water and Bassenthwaite Lake. Data from the gauging stations on the Derwent at Ouse Bridge and the Cocker at Southwaite Bridge suggest combined peak flows of over 580 $m^3 s^{-1}$ would have converged upon Cockermouth between 01:00 and 02:00 on the 19th November.

The temporal and spatial evolution of the flood event that occurred in Cockermouth and Workington was primarily a result of hydrological processes in the upper reaches of the Derwent and Cocker catchments, where the highest rainfall was experienced; this is demonstrated in a series of hourly hydrographs, lake level and catchment average hourly rainfall (CAHR) plots for each catchment (Figure 11). These point to differing hydrological responses within the catchments and CAHR analysis indicates more prolonged intense rainfall across the Cocker catchment over the storm duration. The resulting event hydrograph at Camerton resembles a composite of the two upstream hydrographs, with additional runoff from the intermediate catchment area, especially from the ungauged Marron tributary. This would seem to have received rainfall in excess of 100 mm over the 37 hour period ending at 00:00 on the 20th November (Figure 1) and provides an additional 27.7 km^2 of runoff-generating catchment area. This, with the additional catchment area of the Derwent downstream of the gauged locations discussed, would suggest that the peak flow estimate of 700 $m^3 s^{-1}$ at Camerton is plausible. Catchment rainfall-runoff modelling of the additional areas should, however, be undertaken to validate the additional 120 $m^3 s^{-1}$ estimated to have been generated downstream of gauged locations.

The magnitude of the peak flow of 700 $m^3 s^{-1}$ recorded at Camerton (75002) can be put in the context of other major floods in the UK by a comparison of discharge relative to catchment area. Figure 12 shows the maximum recorded flow plotted against catchment area for over 1,300 gauging stations in the UK, as published in the UK hydrometric register (Marsh & Hannaford 2008), as well as for 68 historical floods listed by Acreman (1989). The plot also features peak flows for two major recent floods, autumn 2000 and summer 2007, using maxima reported by Marsh & Dale (2002) and Marsh &

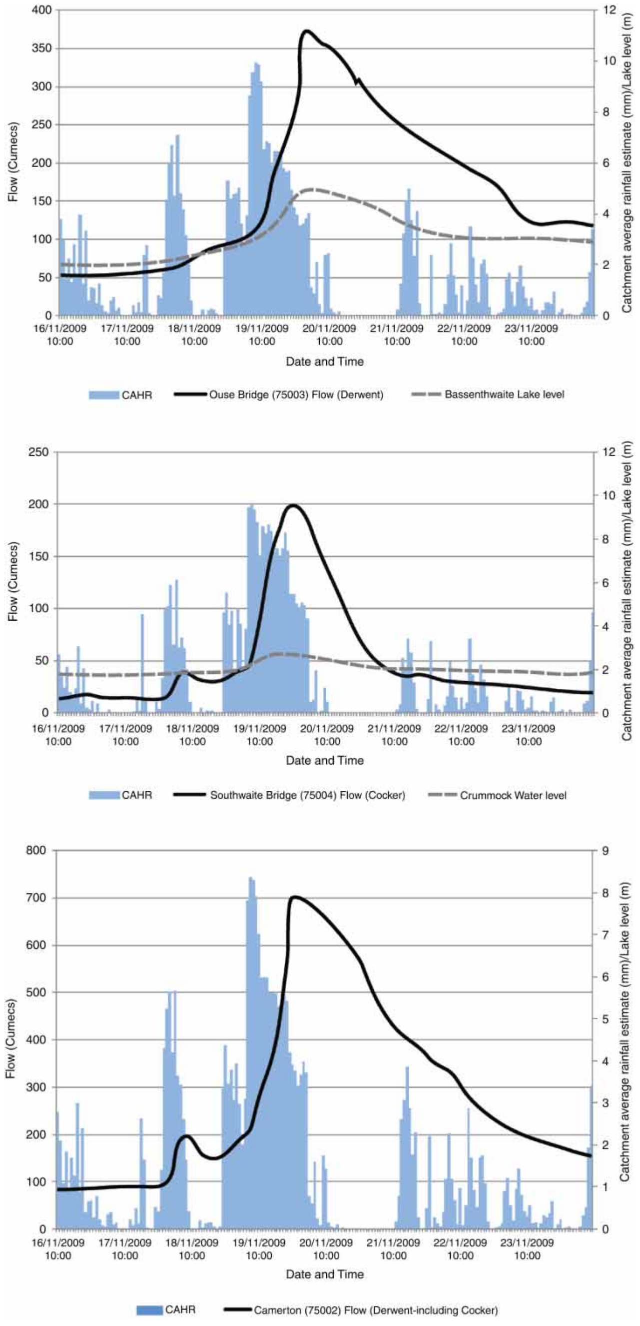

Figure 11 | Catchment hydrograph, lake level and CAHR for Derwent and Cocker catchments over the period 10:00 16/11/2009 to 09:00 24/11/2009.

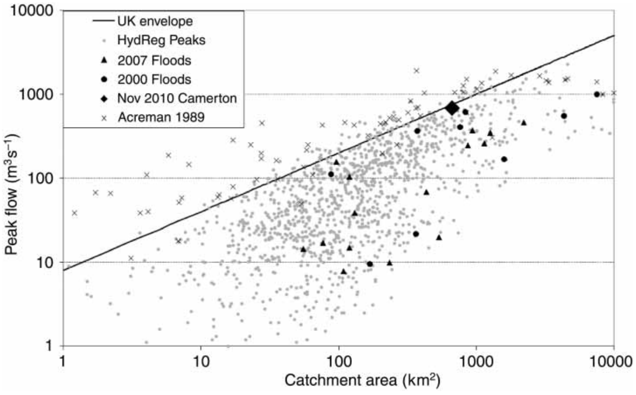

Figure 12 | Maximum recorded flow in relation to catchment area for 1300 UK gauging stations contained within the UK hydrometric register (Marsh & Hannaford 2008) and 68 historical floods at un-gauged UK locations (Acreman 1989); plus Herschy (2002) UK flood envelope curve.

Hannaford (2008), and the UK flood envelope curve of Herschy (2002).

DISCUSSION

The analysis presented in this paper shows that in November 2009, the usual flood-attenuating effect of the Lake District's lakes seems to have been much reduced as a result of their very high water levels. The results of three different methods of analysis support this observation: firstly a comparison of the effect of Bassenthwaite Lake on the River Derwent flood hydrograph in November 2009 compared with that for the next highest recorded flood, in 2005; secondly an analysis of the relationship between lake level and downstream flood peak; and thirdly a comparison of the November 2009 flood hydrograph with previous flood hydrographs for lake-influenced and non-lake-influenced catchments. To further investigate this apparent effect it is recommended that the region-wide overview presented herein is consolidated with more detailed and localised studies – for example, site-based topographic surveys and modelling studies using numerical hydraulic models of the Lake District lakes – to enable a more rigorous appraisal of the role of the individual lakes. The authors note that as a result of this event, the Environment Agency has commissioned the development of a combined 1D/2D model of the Derwent system (Spencer 2011). An aspect not considered in this paper is the role of wind. On very large lakes this can have a considerable effect: for example, on 8 December 1927 winds over Lake Erie, USA resulted in a doubling of the flow in the outflowing Niagara River (Bruce & Clark 1966). For completeness, it is recommended that the role of wind on the response of the Lake District lakes should be quantified. To widen the applicability of these findings, a comprehensive literature search could be conducted on the flood-attenuating properties of lakes; UK and international flood event databases should be searched for other examples of very large floods in lake-influenced catchments.

If it is the case that some lakes behave radically differently at high water levels, this could present difficulties for the FEH statistical method for flood frequency estimation, which for extreme floods usually relies on extrapolating trends from observed, smaller floods. This appears to have been the case on the Derwent at Camerton, where the inclusion of the November 2009 flood caused the estimated return period of a 700 $m^3 s^{-1}$ flood to shorten from 104,181 to 2,102 years. Given the paucity of observations of very high floods on lake-influenced catchments, it might be worth trying an alternative approach in a future version of FEH, whereby the lake effect is applied as an adjustment to a flood estimate, in a similar way to which urban adjustments are currently applied.

The November 2009 flood will have resulted in increases to the estimated 100-year and 1,000-year floods at many places in the Lake District, principally locations downstream of lakes, and at other ungauged lake-influenced catchments elsewhere in the UK whose pooling groups include any of the affected Lake District gauging stations. For example, at Camerton the estimate of the 100-year flood by a standard pooled analysis has increased from 356 to 432 $m^3 s^{-1}$, and for the 1,000-year flood from 453 to 625 $m^3 s^{-1}$. This will feed through into revisions to the national flood maps produced by the Environment Agency, SEPA and the Rivers Agency of Northern Ireland, with possible effects on planning decisions and insurance terms.

Even with the new, reduced estimates of the return period for the November 2009 event, it is still clear that flows were of a magnitude that would not be contained by flood defences of the usual one in 100-year standard. Estimates from the improved FEH statistical method at the gauging stations upstream of Cockermouth suggest a return period of 1,386 years on the Derwent and 769 years on the Cocker. Their combined flow, as indicated by the result for Camerton, was even rarer.

This paper has shown that the Camerton flood peak estimate is plausible. However, given the scientific and historical importance of this event, it would be worth trying to refine this estimate and that at any of the other gauges in the region at which the flow exceeded the measuring capability. The peak flow at Camerton plots broadly along the Herschy UK flood envelope curve (Figure 12), but the UK 2000 and 2007 floods do not appear as extreme using this approach. It is also clear that there are many historical events listed by Acreman (1989) which had a much greater specific discharge than the November 2009 event, or the UK envelope in general. Thus, whilst the peak flow is exceptional for the Derwent catchment and is clearly at the upper expected limit of peak flow for a catchment of this size, in a wider context it is eclipsed by many historical floods. However, the Acreman (1989) approach features flood peaks reconstructed from hydraulic analysis at ungauged locations, whereas the other featured events are all recorded at gauging stations. Many of the events featured in the analysis of Acreman (1989) are from intense storms on small catchments (with many coming from sub-catchments affected by the 1952 Lynmouth flood), whereas the 2009 Cumbria event is notable for its duration and spatial extent as well as the magnitude of the flooding.

Inevitably, such exceptional flood events prompt speculation that climate change is a causal factor. Clearly, it is inappropriate to attribute a single event to climate change, but there is a need for further observational evidence to assess whether flood magnitude or frequency is changing. Whilst the evidence for any compelling long-term increase in fluvial flooding in the UK is equivocal (Robson 2002; Hannaford & Marsh 2008), intense rainfall has increased in the recent past, particularly in some upland areas, including Cumbria (Rodda *et al.* 2010; Burt & Ferranti 2011), and there is some evidence for an increase in high flows and flood frequency in maritime, upland areas of the north-west of the UK (Hannaford & Marsh 2008). An assessment of whether the November 2009 floods are part of an increasing trend is beyond the scope of this paper, but the assessment of rarity presented herein is an important precursor of any future attempt to establish the likelihood of events of a given return period occurring under future scenarios of climate change. Future work may consider the extent to which the event can be attributed to anthropogenic warming, as carried out for the autumn 2000 floods (Pall *et al.* 2011).

CONCLUSIONS

As a result of prolonged record-breaking rainfall over 19–20 November 2009, river flows exceeded previous recorded maxima at 17 gauging stations within Cumbria, many of which were downstream of catchments influenced by lakes. The most extreme rainfall and resultant runoff was experienced within the Derwent and Cocker catchments, causing significant damage to the towns of Cockermouth and Workington and to several gauging stations in the Derwent catchment.

The Environment Agency's estimate of 700 $m^3 s^{-1}$ for the flood peak on the Derwent at Camerton is not inconsistent with recorded river flows at upstream gauging stations.

The estimated return period, from the improved FEH statistical method, of the flood peak at Camerton is 2,102 years; the associated 95% confidence limits are 507 and 17,706 years. The flood has resulted in a major reduction in the estimated return periods of large floods in the Derwent catchment and increases in the estimated size of floods of a specified return period.

It looks likely that this flood was strongly influenced by the record high lake levels, which appear to have reduced the ability of the lakes to attenuate inflowing flood flows. It is recommended that further research is undertaken on this aspect, and that flood frequency estimation procedures in lake-influenced catchments are reviewed.

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