A multi-scale nested experiment for understanding flood wave generation across four orders of magnitude of catchment area

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ABSTRACT

Current understanding of flood response is deficient concerning the variation of flood generation at different spatial scales as a function of spatial and temporal variations in storm rainfall. This study therefore investigates the relationship between rainfall spatial variability and flood response through a multi-scale nested experiment. Hydrological data from an extensive network in the Eden catchment, UK, were collected for a range of flood events over varying scales from 1.1 km^2 to 2,286 km^2. The data were analysed to show the spatial scale dependency of flood peak and lag time. Peak specific discharge for winter events appears to remain constant with area up to 20–30 km^2, corresponding to the main upland headwater catchments, thereafter declining as area increases. The flood response to the convective storms depends on the location of the rainfall and the downstream rates of change of runoff and peak discharge can vary significantly from the winter storm relationships. Particularly for large synoptic storms, average scaling laws for peak discharge have been quantified (exponents ranging between 0.75 and 0.86), illustrating the non-linear nature of the cross-scale variations. Such laws provide a means of linking the headwater catchments with the larger scale at which planners and decision-makers operate.

Key words | catchment area, catchment lag times, flood peak, hydrological scaling, rainfall event, rainfall map

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INTRODUCTION

A major concern in the reliability of flood forecasting models is the accuracy of the rainfall input (Beven 2000). Rainfall is the primary input to most hydrological systems, and a key issue for hydrological science and practice is to assess the importance of the spatial structure of rainfall and its representation for flood runoff generation (Segond *et al.* 2007; Lobligeois *et al.* 2014). In particular, an accurate assessment of the effect of spatial rainfall variability on stream flow is important for understanding the characteristics of catchment response (Singh 1997; Ayalew *et al.* 2015). However, the process of transformation of rainfall to stream flow is complex and the transformation varies with catchment size. Rainfall is variable in space and time depending on the scale of the storm, which varies from the synoptic (large scale frontal systems) to the convective event. Within a catchment, rainfall spatial and temporal characteristics are important in headwater flood generation and the subsequent propagation of the flood through the larger spatial scales (e.g., Paschalis *et al.* 2014). However, the effect of the random spatial variability of rainfall–runoff coefficient and hillslope overland flow velocity on the runoff response decreases with increasing spatial scale (Ayalew *et al.* 2014).

Most catchment experiments have investigated spatial variation in flood response at either the plot/hillslope scale (and applied upscaling) or the catchment scale (and

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applied downscaling). Within the UK, for example, much of the field-based understanding of flood generation has come from experiments at scales of 10 km^2 or less and, because of the non-linear relationship between hydrological response and spatial scale, does not provide a sound basis for extrapolation to larger scales. This is a typical trend for many humid northern latitude catchments. The process by which flood generation in small headwater catchments builds up into floods at larger scale catchments is therefore still poorly quantified. A challenge remains in hydrology to 'bridge the scaling gap', for example, by the application of a multi-scale nested catchment experiment extending to an appropriate scale. Dense instrumentation within such a multi-scale catchment experiment can provide valuable information for understanding hydrological scaling processes and improving model simulations. However, there is a shortage of dense multi-scale nested experiments with sufficient storm and flood data linking the hillslope to the full catchment scale. Ayalew *et al.* (2015) note that apart from theirs, only two studies have been conducted using solely empirical data sets in an effort to explore physical processes that control flood scaling parameters (considering event dynamics). All of these studies have been conducted in the USA.

A means of upscaling peak discharge from a small catchment to a large catchment would be useful in flood prediction, design of riparian and in-channel infrastructure, environmental impact assessment and other water resources activities. Numerous studies have found that peak discharge shows a power law variation with catchment area (e.g., Smith 1992; Gupta *et al.* 1994; Goodrich *et al.* 1997; Ogden & Dawdy 2003; Furey & Gupta 2005, 2007; Mandapaka *et al.* 2009; Ayalew *et al.* 2014, 2015), i.e.:

$$Q_p = aA^k \tag{1}$$

where Q_p is peak discharge, A is catchment area, a is a coefficient and k is the scaling exponent. Typically, k is less than 1, with published values often being in the range 0.5–0.8. However, a number of factors determine the exponent, including rainfall rate, space-time variability in the channel network (channel conveyance and network routing), soil moisture and infiltration capacity, groundwater table elevations, land use and land cover and geomorphology. The significance of these factors depends to a great extent on the runoff production mechanism and the scale of the catchment (Ogden & Dawdy 2003). Scaling effects of other hydrological processes are also likely to be important, notably in the rainfall.

While most simulations and data-based studies have focused on the scaling of annual peak flows, there are some examples of research studies investigating single event peak flows (e.g., Gupta *et al.* 1996; Ogden & Dawdy 2003; Furey & Gupta 2005, 2007; Mantilla *et al.* 2006; Mandapaka *et al.* 2009). The physical mechanism responsible for scale-invariance can be identified much more precisely for individual rainfall–runoff events (Mandapaka *et al.* 2009). Ogden & Dawdy (2003) observed that peak stream discharge and drainage area for individual rainfall–runoff events in the 21-km^2 Goodwin Creek Experimental Watershed (GCEW) in Mississippi are related, on average, by the power law (Equation (1)). It was also observed that a and k changed from event to event. This discovery showed for the first time that spatial power laws in peak discharge are present in a real catchment on an event-by-event basis (Furey & Gupta 2007). Furey & Gupta (2007) also found, on analysis of 148 events in the GCEW, that α and k change because of corresponding changes in depth, duration and spatial variability of excess rainfall (that is, rainfall that is not held on the land surface or infiltrates into the soil). However, the scale of this catchment is relatively small and event data on peak discharge scaling from the hillslope to the larger catchment scale are limited. Ayalew *et al.* (2015) extended the analysis to the Iowa River basin (32,000 km^2) for a range of flood events and noted that the temporal and spatial structure of the rainfall affects the scaling structure of the flood peak. The paper focused on five orders of magnitude of area and large scale storm events. A limitation of the research was that it analysed only flood events which resulted from basin-wide rainfall events and omitted partial rainfall coverage events (rainfall values were determined using radar data). There is a further need to investigate flood peak scaling relationships in different climatic regions and landscapes, considering all storm types and rainfall coverages.

A key question is how spatial variability in rainfall affects the flow response at the catchment scale (Bell & Moore 2000). This relationship may be important for flood warning procedures operated in real-time or may form a key role in the design and planning of flood defence measures (Bell & Moore 2000). Addressing the question requires high quality rainfall data as well as an understanding of rainfall processes over different scales. The aim of this paper is therefore to investigate the relationship between rainfall spatial variability and flood response across a range of catchment scales, through a multi-scale nested catchment experiment. Hydrological data from an extensive, nested hydrometric network in the predominantly rural upper Eden catchment, Cumbria, UK, were collected for a range of flood events, including winter frontal, summer convective, multi-peak and single peak events. The data were analysed to show the spatial scale dependency of flood peak and lag time for the different events. The study is a rare example of field scaling pursued across four orders of magnitude of area (1–1,000 km^2). It is innovative in its use of an unusually densely instrumented multi-scale network and its analysis of spatial variations of hydrological response for a range of storm types. In this way, the study is able to contribute significant new material to the literature on flood-peak scaling-law parameters. Worldwide, rainfall-generated floods pose a major risk and there are concerns that this risk will only increase with global warming. Therefore, the results of the study are relevant to the increasing demand for development of flood warning, protection and mitigation measures.

METHODS

Study site and data network

The upper Eden catchment was a multi-scale nested experiment used to investigate the relationship between rainfall spatial variability and flood response. The experiment was set up as part of the Catchment Hydrology And Sustainable Management (CHASM) programme (2003–2007), which was established to gain a new understanding of the hydrological and ecological functioning of mesoscale catchments (10^2–10^3 km^2) and of how catchment response changes with scale, and to translate this new knowledge into enhanced predictive capability (O'Connell *et al.* 2007; Wilkinson 2009). The Eden catchment is located in northwest England (Figure 1, left), between the Lake District mountains to the west and the Pennine hills to the east, and covers 2,286 km^2 to its outlet near Carlisle at the Solway Firth, which leads to the Irish Sea. The upper catchment is located in the south east and is defined by the Environment Agency (EA) for England gauging station at Temple Sowerby (616 km^2). Within the upper catchment, four main headwater catchments combine over a short reach of the Eden just upstream from the EA's Great Musgrave gauging station (222.5 km^2): the main stem of the upper Eden, Swindale Beck, the River Belah and Scandal Beck (Figure 1). In the upper catchment the uplands consist of Millstone Grits (coarse-grained sandstone) that generally lie over carboniferous rocks (sequences of limestone, sandstones and shales). Where the limestone is prominent (lowlands), karstification of the rock produces high yielding aquifers. However, the prominent aquifer on the valley floor (lowlands) is the sandstones, which sit on top of the limestone series. Land use in the upper Eden catchment is predominantly livestock farming (sheep and cattle). The upland is characterised by rough moorland, moorland, unimproved pasture and peat mires. The lowland areas of the catchment are generally improved pasture and hay meadows. The upper Eden has four different soil type series: the Winter Hill series (a black, semi-fibrous peat surface with a reddish brown-coloured peat deeper down) cover the upland moors of Mallarstang common (far south) and the Warcop fells (east). The catchment to Kirkby Stephen (Figure 1, right) is predominantly covered by the Eardiston 1 Association (reddish well-drained coarse loamy and fine silty soils) in the upland areas and the Wick 1 Association (dark-yellow brown, slightly stony sandy loam or sandy silt soil; common in northern England) along the valley floor and low lying areas (Walsh 2004). From Kirkby Stephen to Temple Sowerby the valley floor and low lying areas are covered mainly by the Clifton Association (sandy loamy). The upper Eden catchment receives a yearly average of 735 mm to 2,590 mm of precipitation depending on the location.

During the study period of autumn 2003 to summer 2007, the upper Eden catchment had an unusually dense hydrometric network, consisting of up to 25 tipping bucket raingauges (TBR), three weather stations and eight nested stage gauging stations, strategically placed over the 616 km^2 catchment (Figure 1, right). The existing EA

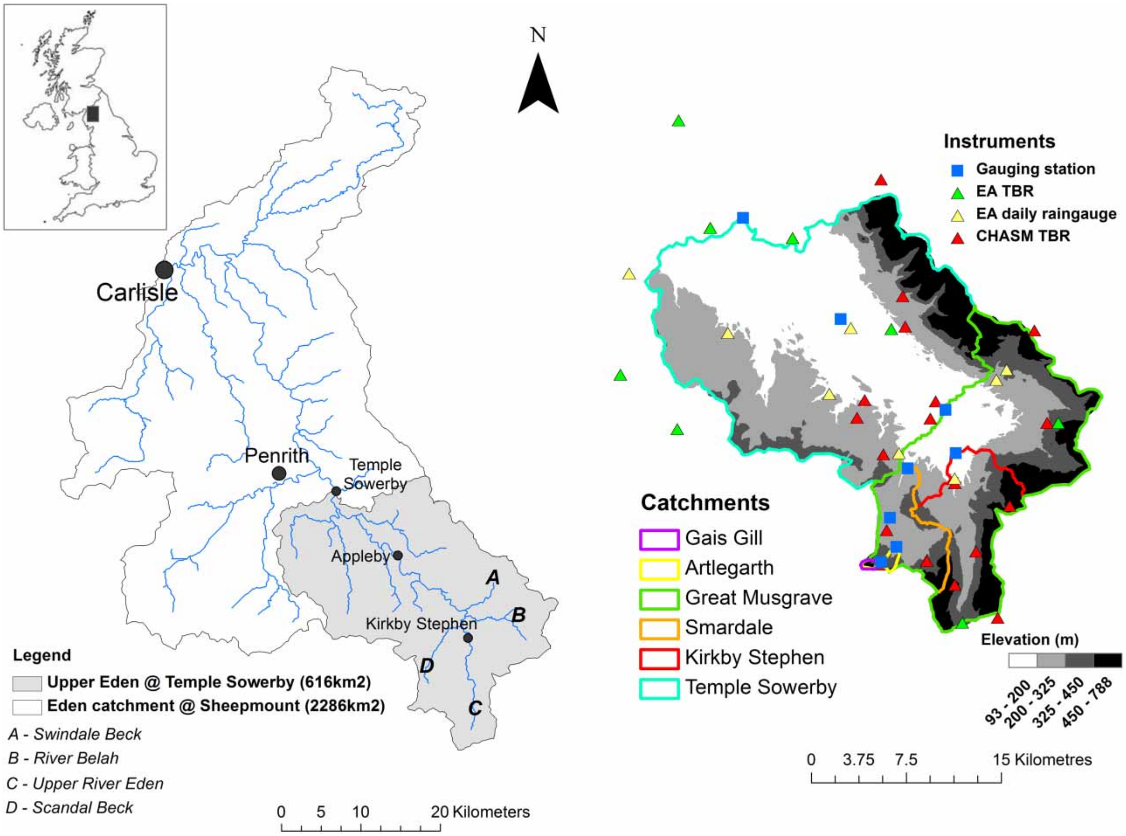


Figure 1 | (Left) location map for the full Eden catchment (2,286 km^2) and (right) the upper Eden CHASM hydrometric network above Temple Sowerby (616 km^2).

raingauge network consisting of nine raingauges (five daily collection gauges and four TBRs) was biased towards the lowlands downstream of Kirkby Stephen and most raingauges were daily collection gauges. The CHASM raingauges were deployed so that they would increase the spatial coverage (by filling gaps between existing raingauges). Most notably, they extended measurements to higher elevations (up to 850 m above sea level). To support the scale analysis, CHASM river stage data from Gais Gill, Artlegarth Beck, Ravenstonedale and Smardale are presented here along with data from the EA gauging station network along the Eden itself (Kirkby Stephen, Great Musgrave and Temple Sowerby) (Table 1). For flood peak scaling analysis two additional EA gauging stations along the main stem of the Eden (Great Corby, 1,371 km^2 and Sheepmount (Carlisle), 2,286 km^2) are used (Table 1, Figure 1). Flows at these stations are augmented by tributaries draining the Lake District. The eight stations apart from Kirkby Stephen

Table 1 | Multi-scale nested catchments within the Eden catchment (including catchment descriptors)

Catchment	Catchment area (km^2)	Standard average annual rainfall (mm)	Base flow index[a]	Standard percentage runoff[b] (%)
Gais Gill	1.1	1,897	0.36	49.1
Artlegarth	2.7	1,819	0.35	46.6
Ravenstonedale	25.6	1,625	0.44	41.7
Smardale	36.6	1,516	0.50	37.7
Kirkby Stephen	69.1	1,492	0.41	45.8
Great Musgrave	222.5	1,270	0.44	42.4
Temple Sowerby	616.4	1,142	0.47	37.0
Great Corby	1371	1,272	0.51	36.9
Sheepmount	2286	1,182	0.49	37.8

[a] Baseflow index.

[b] Standard percentage runoff is based on Hydrology of Soil Types (Boorman *et al.* 1995).

form a nested sequence down a major headwater tributary and then the main stem of the Eden, spanning scales from 1 km^2 to over 1,000 km^2. Kirkby Stephen lies on the main stem of the upper Eden and is nested within the sequence from Great Musgrave downstream. Stream gauges recorded level data at 15-minute intervals. TBR tips were also aggregated at 15-minute intervals.

Data analysis

The aim of the analysis was to examine the downstream variation of the flood hydrograph as a function of the spatial and temporal variability of the influencing storm, and thus to determine the scale dependencies in hydrograph properties for a range of storm types and magnitudes. The analysis therefore considers the storm characteristics, the magnitude of the flood peak within the nested catchment system, runoff generation and the hydrograph lag time (defined as the time from the centroid of the rainfall storm to the peak discharge at the catchment outlet). A power regression statistical model was used to explore the relationship between (a) peak runoff, (b) lag time and (c) peak discharge and catchment area (Equation (1)) for each individual event. For the flood peak scaling analysis the resulting exponent was calculated by grouping (i) all events, (ii) antecedent conditions prior to the storm (wet vs dry), (iii) storm type (convective vs synoptic) and, finally, (iv) for each individual event. Lag time variations between catchments are usually different owing to geomorphological characteristics such as geology, catchment shape and network design. However, hydrological and climatological factors may cause a catchment lag time to change depending on the storm pattern and the hydrological properties of the catchment. In this case the lag time is examined for numerous storms at differing catchment scales. In calculating lag time, the rainfall centroid was derived from the average storm hyetograph in each nested sub-catchment examined (using raingauges available only in the examined sub-catchment and excluding out-of-catchment raingauges). The outlet discharge peak was the instantaneous peak (based on 15-minute stage records). The analysis is limited to the Eden catchment above Temple Sowerby (616 km^2) as the rainfall data available to the study did not extend to the larger catchment areas. Return periods at the EA gauging sites were calculated using the Flood Estimation Handbook Generalised logistic distribution method, which is recognised as the best practice method for estimating peak flood discharge (Centre for Ecology and Hydrology 1999).

During the study period the instrumented network experienced a cluster of large flood events. This study focuses on six periods of flooding, ranging from minor to substantial floods. These are the largest recorded synoptic and convective scale events during the study period (i.e., approximately the QMED (i.e., 1 in 2 year return period peak flow) or greater recorded at Temple Sowerby during the study period). Although the study is limited to these monitored events, they represent a range of monitored high flow flood events, all of which are the largest record synoptic and convective scale events during the study period. Two extreme flood events which occurred after the CHASM programme finished are then compared against the larger multi-scale network, albeit with a reduced network starting at a larger catchment scale. Discharge data are available for nearly all the events from most gauging stations during the study period. Some floods, however, damaged some of the stage recorders, leaving gaps in some of the data records.

Data errors may have occurred in storm rainfall totals and high flow discharges. Synoptic storm events in the field area are characterised by strong winds, which in some cases reached hurricane force on the Beaufort scale (and once blew away the anemometer cups). This resulted in significant raingauge undercatch, especially for the higher elevation sites, and generally there remains an urgent need to estimate rainfall in high wind conditions more accurately. Likewise, the stage-discharge rating curves for the CHASM gauging stations were not always as well defined for high flows as was desirable, creating uncertainty in some peak discharge values. This was less of a problem for the EA gauging stations, for which the greater length of record allowed better defined rating curves.

RESULTS AND ANALYSIS

Overview of storm events

Two types of storm occur in the upper Eden catchment: synoptic scale events and convective storm events. Synoptic scale events are the most common and develop as moist frontal systems move off the Atlantic Ocean into the catchment regularly during the winter months. Convective storm events are less common and occur mostly in the summer months, potentially causing localised flooding. Figures 2–7 show the spatial and temporal variation in rainfall and runoff response for the six periods of flooding recorded during the study period. The exceptional detail of the rainfall distribution maps in particular are testament to the unusually dense hydrometric network. The maps were produced using inverse distance weighting in ArcGIS 9.3 software to interpolate between the point gauge sites.

Event 1 (Figure 2) is a small flood event which occurred on 26th December 2003 and caused localised flooding in the headwaters. The hydrograph for the Gais Gill catchment is flashier than the hydrographs for the other gauging points, indicating that runoff generation for this event is greatest in the uplands.

Event 2 (Figure 3) comprised a sequence of five flood peaks, two of which were notably large. The 3rd February flood peaked at 291 $m^3 s^{-1}$ at Temple Sowerby and had a return period of 9.7 years at Kirkby Stephen. An examination of these floods can be found in Mayes *et al.* (2006). This is an example of a multiday event in which the first events saturate the catchment, enabling the later storm events to generate significant runoff.

Event 3 was caused by a large depression which moved over the Eden catchment producing intense precipitation and resulting in one of the largest floods on record. It is very unusual to receive large amounts of precipitation simultaneously on both the Lake District and the Pennines (Guy Carpenter Ltd 2005); the resulting runoff could not be contained within the banks and severe flooding occurred in Carlisle. Peak discharge values of 2.2 and 194 $m^3 s^{-1}$ were recorded at Gais Gill and Great Musgrave, respectively (Figure 4). The estimated return periods were 19 years at Kirkby Stephen and 240 years at Temple Sowerby. Event 1 (Figure 2) is similar to Event 3 in that it was a single peak event (at the larger scales). However, discharge and rainfall totals were around half those of Event 3 and the flood peak return periods at all sites were similar to the mean annual flood.

Event 4 (Figure 5) caused little flooding. The series of floods was the result of one of the wettest starts to December on record. Six flood peaks occurred over a 15-day period, a

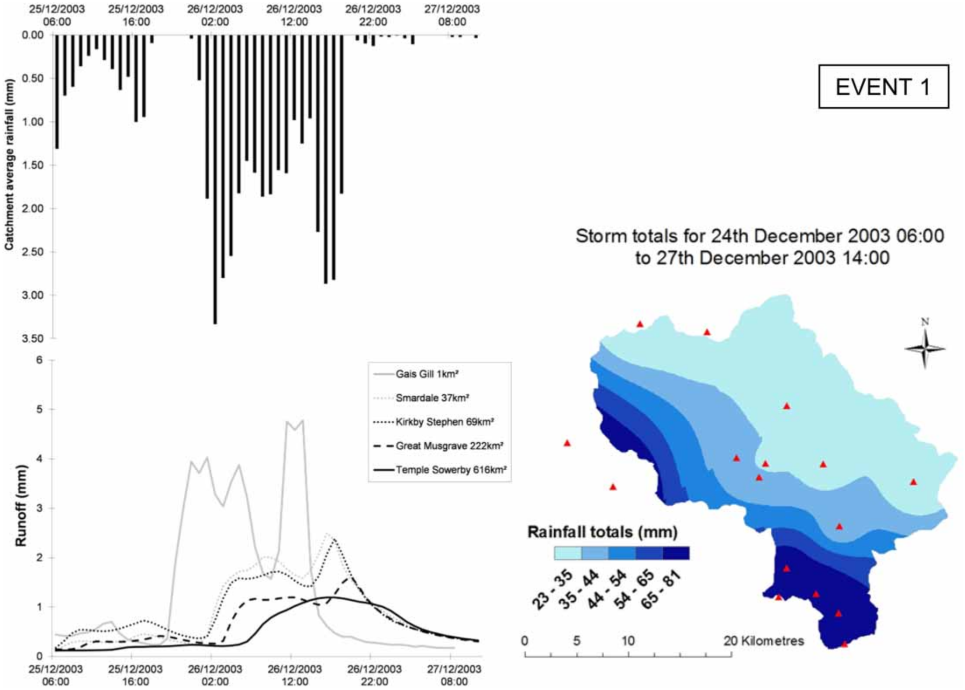


Figure 2 | Catchment average rainfall (mm/hr) versus discharge (expressed as runoff) at Gais Gill (1.7 km^2), Smardale (37 km^2), Kirkby Stephen (69 km^2), Great Musgrave (222 km^2) and Temple Sowerby (616 km^2) (left) over the 26th December 2003 event (right) (Event 1).

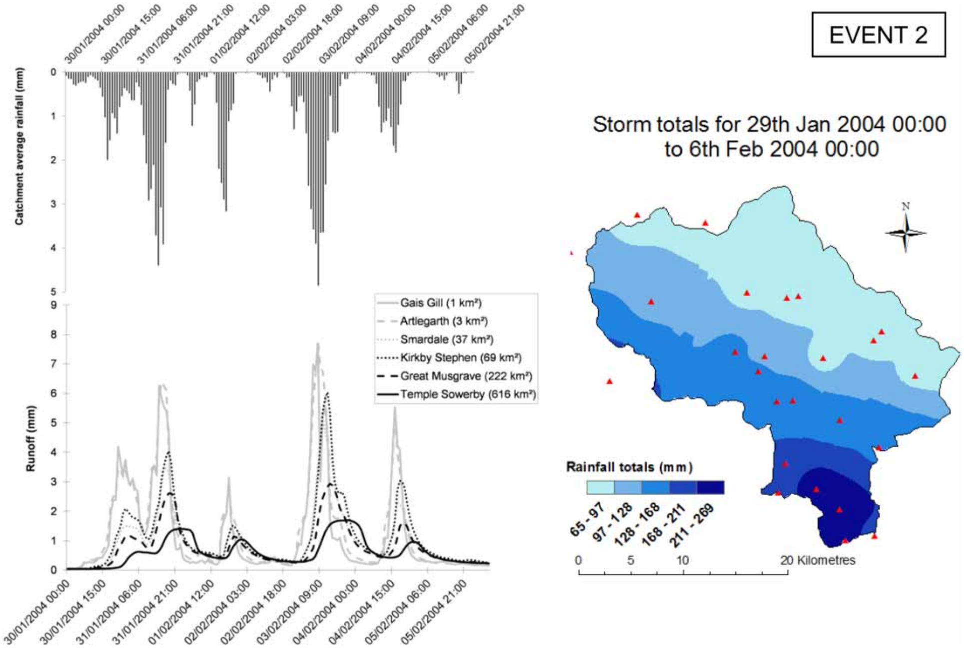


Figure 3 | Catchment average rainfall (mm/hr) versus discharge (expressed as runoff) at Gais Gill (1.7 km^2), Smardale (37 km^2), Kirkby Stephen (69 km^2), Great Musgrave (222 km^2) and Temple Sowerby (616 km^2) (left) over the multiday February 2004 event (right) (Event 2).

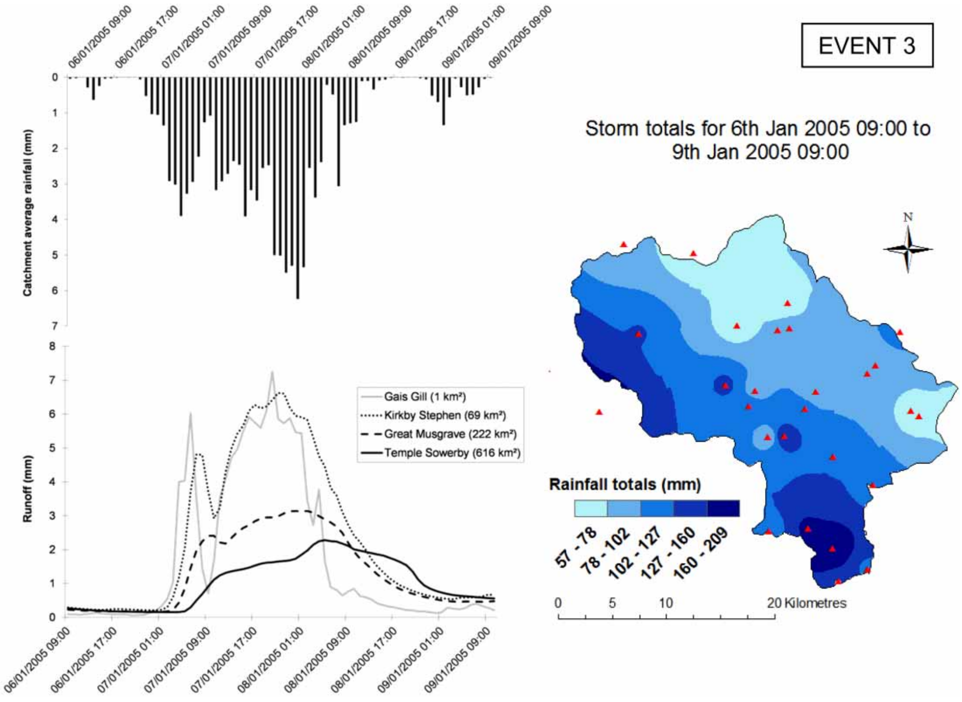


Figure 4 | Catchment average rainfall (mm/hr) versus discharge (expressed as runoff) at Gais Gill (1.7 km^2), Kirkby Stephen (69 km^2), Great Musgrave (222 km^2) and Temple Sowerby (616 km^2) (left) over the extreme January 2005 event (right) (Event 3).

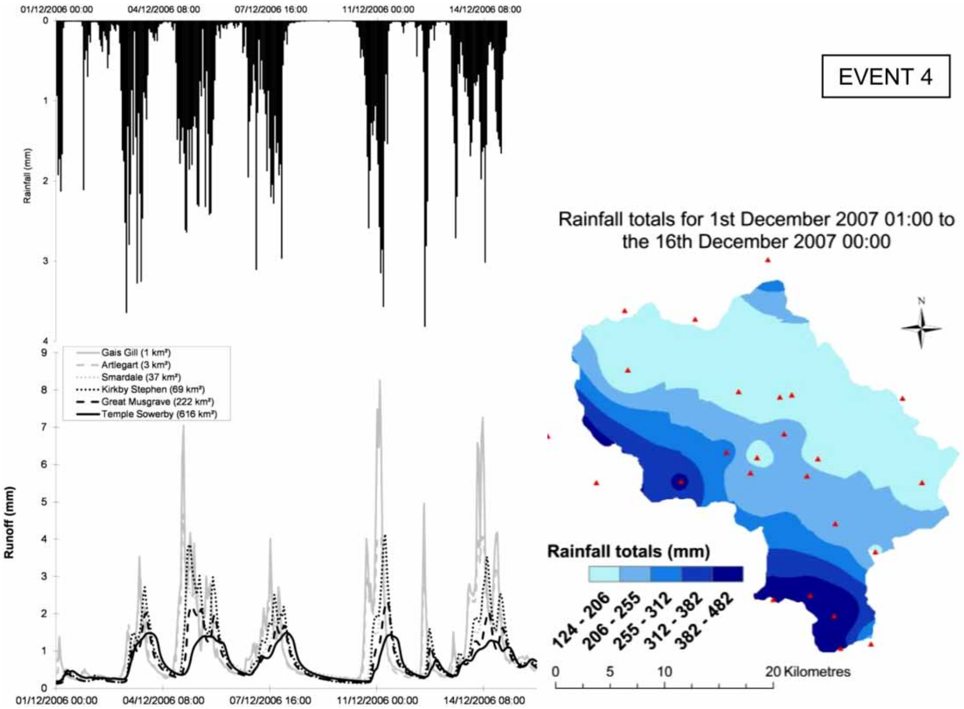


Figure 5 | Catchment average rainfall (mm/hr) versus discharge (expressed as runoff) at Gais Gill (1.7 km^2), Artlegarth (2 km^2), Smardale (37 km^2), Kirkby Stephen (69 km^2), Great Musgrave (222 km^2) and Temple Sowerby (616 km^2) (left) over the 14 day December 2006 event (right) (Event 4).

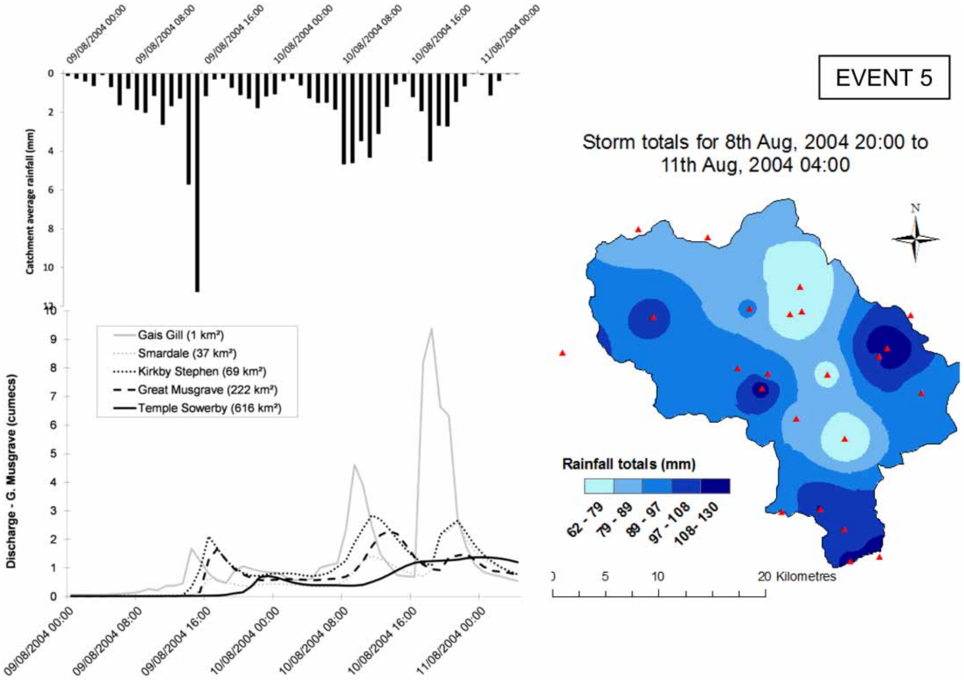


Figure 6 | Catchment average rainfall (mm/hr) versus discharge (expressed as runoff) at Gais Gill (1.7 km^2), Smardale (37 km^2), Kirkby Stephen (69 km^2), Great Musgrave (222 km^2) and Temple Sowerby (616 km^2) (left) over the multi-convective August 2004 storm events (right) (Event 5).

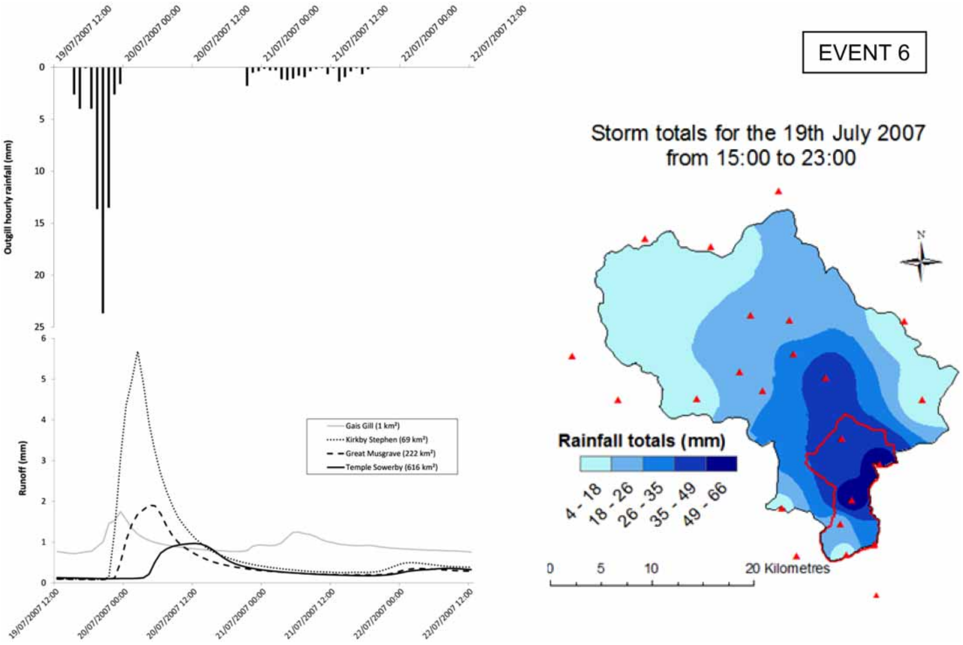


Figure 7 | Catchment average rainfall (mm/hr) versus discharge (expressed as runoff) at Gais Gill (1.7 km^2), Kirkby Stephen (69 km^2), Great Musgrave (222 km^2) and Temple Sowerby (616 km^2) (left) over the localised convective 19th July 2007 event (right) (Event 6).

high density of peaks. All of the storms were the result of depressions crossing the Eden catchment and most were similar in size. The largest storm rainfall occurred on 5th December but the largest flood discharge occurred on 11th December. This shows how the build-up of saturated antecedent soil conditions before the 11th December storm, as a result of three previous storms, caused proportionally increased runoff and a larger flood. However, the intensity of these storms was less and the time gap between events was longer compared with Event 2 (Figure 3).

Event 5 resulted from a series of storms which occurred over 3 days (Figure 6). These events were localised in certain parts of the catchment, notably the north-east and the central-south. The events resulted in localised flooding; however, the peak discharge at Temple Sowerby was not as extreme as in the winter events. Owing to the localised nature of these floods, the return period of the flood peak at Temple Sowerby was similar to the mean annual flood.

Event 6 resulted from a small localised convective storm which caused substantial flooding in part of the Kirkby Stephen catchment. This storm was located over the centre of the Kirkby Stephen catchment and lasted 5 hours (from 18:00 to 23:00) (Figure 7). In the neighbouring nested catchments (Gais Gill, Artlegarth House, Ravenstonedale, Smardale), no major change in level was recorded at the gauging stations as far down as Smardale. The Kirkby Stephen catchment was the only catchment to respond significantly to this storm, with an estimated return period for the storm rainfall of 6.4 years. The only flooding occurred in the small village of Outhgill. Outside the Kirkby Stephen catchment, rainfall totals were small and had little effect on river levels. At Kirkby Stephen the discharge peaked at 110 $\mathrm{m^3\,s^{-1}}$, while a little later at Great Musgrave it peaked at 118 $\mathrm{m^3\,s^{-1}}$ (Figure 7). The Great Musgrave flood peak was the result of the Kirkby Stephen catchment output plus background flows from other catchments.

Event spatial and temporal characteristics

The rainfall maps in Figures 2–7 enable spatial rainfall patterns to be identified as a function of event type and spatial scale and these patterns can then be related to the flood characteristics. The most obvious contrast is between the generally similar patterns of the synoptic rainfall events and the more individual and less uniform patterns of the summer convective storms (Figures 2–7 and Table 2).

Table 2 | A summary of the characteristics of the six main storm events

Event	Date	Event type	Rainfall [min-max] (mm)	TS peak runoff (mm)	Duration	TS *Qp* (m^3/s)	TS return period (yr)
1	26/12/2003	Synoptic (single peak)	22–101	1.2	3 days	205	1
2a	30/01/2004	Synoptic (multi- peak)	60–270	1.4	5 days	240	1
2b	02/02/2004	Synoptic (multi- peak)	60–270	1.7	(as above)	291	6.4
3	07/01/2005	Synoptic (single peak)	53–204	2.4	42 hours	925	240
4	11/12/2006	Synoptic (multi- peak)	113–511	1.4	15 day	245	2
5	10/08/2004	Convective (multi-event)	64–116	1.4	3 days	236	1
6	19/07/2007	Convective (single)	0–66	1.0	5 hours	166	1

TS, Temple Sowerby.

Synoptic events (Events 1–4)

For the synoptic events the rainfall depths show a gradation from the highest values in the south and west to lower values in the north and east. This corresponds to the orographic effect of the high ground to the west and the rain shadow effect over the rest of the catchment. Within this general pattern, though, there are distinct differences in temporal distribution and magnitude that result in different runoff responses between the events. Events 1 and 3 (Figures 2 and 4, respectively) were essentially single storm events occurring over relatively short periods of a day or two but of greatly different magnitude. Event 1 rainfall was concentrated more on the south-western uplands and therefore had a particularly noticeable impact on the upland headwater runoff response (Gais Gill). The effect on the more lowland source areas (Kirkby Stephen) was less pronounced. By contrast, Event 3 rainfall was extreme in both the uplands and the lowlands and the runoff response was correspondingly more uniformly large throughout the catchment. Events 2 and 4 (Figures 3 and 5, respectively) comprised sequences of storm events over periods of a week or more. The runoff responses are generally similar, with the upland Gais Gill catchment showing particularly flashy patterns. Again, though, the greater rainfall in the lowland headwater areas in Event 2 raised the runoff response in those areas in proportion to the Gais Gill response compared with Event 4. The rainfall totals and temporal distribution of Event 3 are similar to those for Event 2 but spread over 2 days rather than the week of the latter case. No raingauges were present in the north of the catchment at this time so the nearest raingauges which are located in the lowlands were used in the interpolation process for the rainfall maps (Figure 1). These may therefore underestimate rainfall on the Pennine slopes.

Convective events (Events 5 and 6)

Figure 6 (Event 5) displays a series of convective rainfall storms. The most intense rainfall was in a small area in the north-east of the upper Eden catchment. The highest flows were probably in Swindale Beck and the River Belah (both ungauged catchments; Figure 1) which drain the slopes of the north-eastern parts of the catchment above Appleby. A large contribution to the peak discharge at Great Musgrave was probably due to flow from these tributaries (and less from the upper Eden and Scandal Beck, which are monitored). However, the raingauge network does not capture the full extent of this localised storm. High rainfall intensities are recorded at only three raingauges and, therefore in the rainfall map, which was derived through interpolation, the high intensity rainfall area may be misrepresented. The intensity of the storm may have been greater further to the north of the catchment. The location of a localised storm in larger scale catchments (such as Great Musgrave) can significantly affect the timing of the resulting flood peak through channel network routing (for example, a localised storm nearer the outlet will have a shorter lag time). The Swindale and Belah catchments have shorter main channel networks compared with the upper Eden catchment above Kirkby Stephen. Therefore any intense rainfall occurring in these catchments will generate runoff at their outlets (just upstream from Great Musgrave) faster. Other factors, such as catchment antecedent conditions, also have an overall effect on runoff generation and thence flood peak timing. Nevertheless, the location of the most intense rainfall in a convective storm will always be the critical factor in flood peak timing.

Figure 7 displays a single convective storm event (Event 6). The spatial extent of the most intense rainfall is smaller than the Kirkby Stephen catchment, at around 25% of the area. It is possible that the storm was larger, covering an area to the east, outside the Kirkby Stephen catchment. Again, though, the raingauge network was not dense enough to capture the full spatial variability of this storm. The rainfall intensity peaked at around 23.7 mm in 1 hour (Outhgill raingauge). The shape of the Kirkby Stephen catchment did not entirely coincide with the storm, with little rain recorded in the south.

Lag time

The importance of lag time can be judged from a comparison of lag times for the Kirkby Stephen and Great Musgrave stations in Table 3. The lag time of the flood peak at Great Musgrave for Event 5 is much smaller than the lag time of Events 1 to 4 (resulting from rainfall from a widespread synoptic scale event). The most intense rainfall for winter flood events usually occurs in the upland headwater tributaries and, for the Great Musgrave catchment, these are mainly in the south of the catchment. The channel network here is relatively extended and therefore routing of the flood peak takes longer. Localised convective events in the north of the catchment produce flood peaks which travel a shorter distance to their catchment outlets just upstream from Great Musgrave. This highlights the importance of storm location in determining the speed of response at the catchment outlet. It is possible that a fast moving, large flood peak in one subcatchment can dominate the effect of a smaller flood peak with a longer time of travel in another subcatchment in terms of the lag time for the combined flow at the catchment outlet.

Table 3 | Summary of flood peak lag time at the Kirkby Stephen and Great Musgrave gauging stations for selected flood peaks from Events 1 to 6

Date of flood peak	Lag time at Kirkby Stephen (min)	Lag time at Great Musgrave (min)
26 December 2003 (Event 1)	165	230
31 January 2004 (Event 2a)	340	350
2 February 2004 (Event 2b)	295	355
7 January 2005 (Event 3)	410	620
9 August 2004 (evening) (Event 5)	300	175
19 July 2007 (evening) (Event 6)	195	300

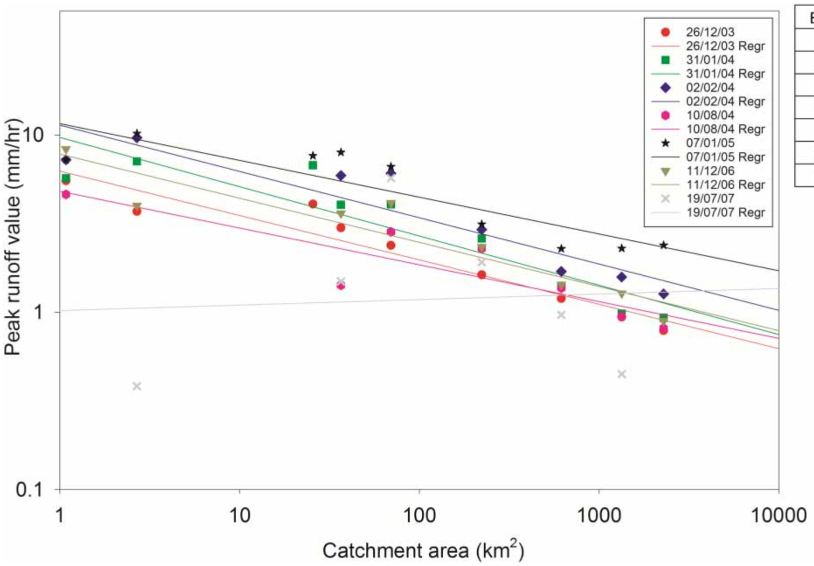
The lag time of Event 6 in the Kirkby Stephen catchment was 195 minutes, one of the shortest lag times of any storm (Table 3). As the Kirkby Stephen catchment is long and thin, the location of a convective storm within the catchment is crucial. This storm was close to the outlet and therefore the lag time was short.

Scaling trends in the catchment

Scaling of catchment runoff peak values

The hypothesis (and well-established theory) is tested that peak runoff declines relative to the high production zone of the upland catchments as increasing catchment size incorporates larger proportions of less runoff-productive lowland areas. The analysis incorporates the larger catchment scale to Great Corby (1,373 km^2) and Sheepmount (2,286 km^2).

Figure 8 shows different scaling patterns depending on the event (however, Event 2 has two notable flood peaks which resulted in flooding); the fitted power regressions refer to the overall response across all the stations. In general, runoff decreases as catchment scale increases, in accordance with the hypothesis. For the winter synoptic events (Events 1–4), the trend is apparent across all sites, as rain fell across the entire catchment. However, in detail, the trends vary as a function of the rainfall pattern. The overall rate of decline is least for Event 3 (fitted exponent $k = -0.14$), reflecting the heavy rain across both upland and lowland. The downstream stations were affected by major discharges from Lake District rivers joining below Temple Sowerby (Figure 1), resulting in a small increase in runoff as area increases. During both peaks of Event 2 exponents are higher, probably owing to the favourable antecedent conditions caused by a small amount of snow melt and frozen ground at the beginning of the storm followed by the further wetting up of the



Event		k	r^2
26/12/2003	**1**	**-0.25**	0.92
31/01/2004	**2a**	**-0.27**	0.84
02/02/2004	**2b**	**-0.26**	0.86
07/01/2005	**3**	**-0.14**	0.73
11/12/2006	**4**	**-0.29**	0.94
10/08/2004	**5**	**-0.32**	0.98
19/07/2007	**6**	**0.03**	0.00

Figure 8 | Runoff peak values as a function of rainfall event and catchment area with power laws fitted to six flood events (with Event 2 shown as separate components of a multiday event).

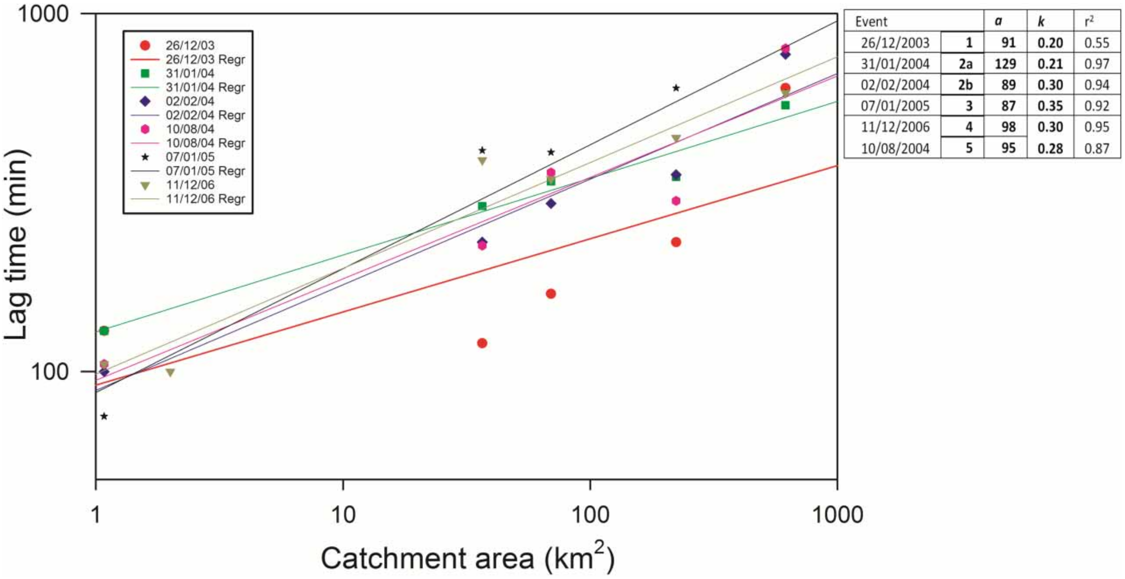
ground. In all cases, the data points indicate a rate of decline that is less in the upland headwaters, to a scale of around 20–30 km^2, than in the main stem of the larger catchments. This suggests a relatively uniform runoff generation throughout the main production area and the area of highest rainfall (which coincide). As catchment area increases, incorporating more lowlands, the distance between runoff production zones and the river system increases and rainfall totals decrease. Runoff then declines at a more rapid rate.

For the summer convective storms (Events 5 and 6), the overall pattern of declining runoff in the downstream direction is maintained for the catchments within which the rain fell. Thus, Event 5 shows an overall decline as it affected all the gauged catchments. By contrast, Event 6 was concentrated in the Kirkby Stephen catchment and largely missed the Gais Gill–Smardale system. Thus, there is a disconnection between this system and the rest of the sites. From Kirkby Stephen down the main stem of the Eden, though, there is a steep decline in runoff, reflecting the localised nature of the storm and the resulting rapid attenuation of the flood wave downstream.

Overall, the results demonstrate both the strong connection between rainfall pattern and runoff generation and the dependency of the downstream rate of decline in runoff on catchment scale, rainfall spatial scale and catchment topography.

Lag time scaling

Lag time is generally expected to increase as the catchment size increases, since the distance to the catchment outlet and therefore the travel time increase. Figure 9 shows that the scaling relationship between lag time and catchment area corresponds to this expectation. Events 2–4 have better model fits, while Event 1 shows rather more scatter. Events 1 and 2a show relatively slow rates of increase in lag time with area (fitted exponents of around 0.20–0.21). This is suggestive of a fast moving flood wave or else a downstream progression of the rainfall event, so that the rainfall centroid occurs later as catchment area increases. The other events (Events 2b, 3, 4 and 5) show a more rapid increase in lag time downstream (exponents around 0.3), suggestive of the opposite effects. In particular, if the rain producing most of the runoff is limited to the upper part of a catchment, so that the rainfall centroid for the upper catchment applies also to the lower catchment, the passage of the flood wave into the lower part inevitably involves a lengthening lag time. Flood wave speed could vary with the antecedent flow levels and the amount of out-of-bank flow but it is not clear



Event		*a*	*k*	r^2
26/12/2003	**1**	**91**	**0.20**	0.55
31/01/2004	**2a**	**129**	**0.21**	0.97
02/02/2004	**2b**	**89**	**0.30**	0.94
07/01/2005	**3**	**87**	**0.35**	0.92
11/12/2006	**4**	**98**	**0.30**	0.95
10/08/2004	**5**	**95**	**0.28**	0.87

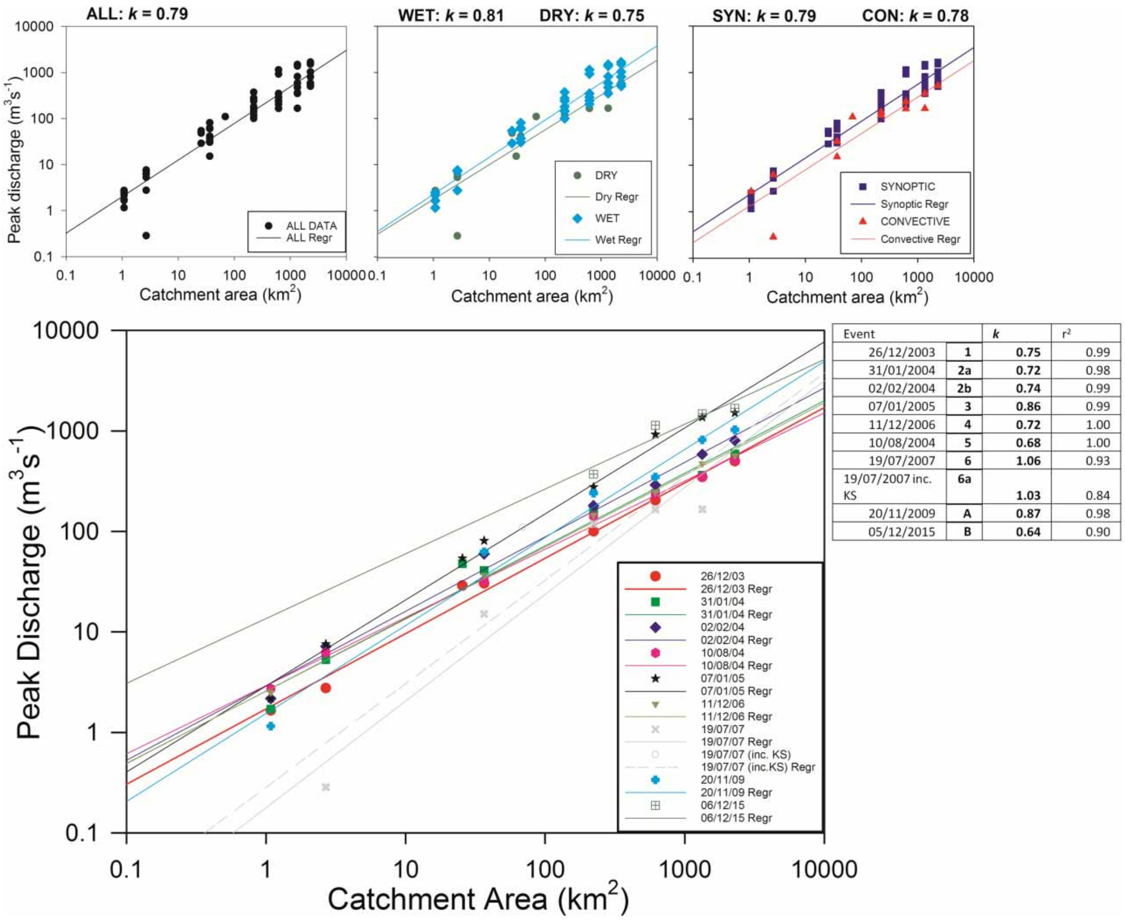
Figure 9 | Lag time plotted against catchment area with power laws fitted to six flood events.

if this could produce the differences observed between events (e.g., difference between Events 2a and 2b). It is more likely, therefore, that the differences in downstream rate of increase in lag time are due to rainfall pattern. Comparison of the two events with lower exponents (Events 1 and 2a) shows significant variation in the coefficients of the fitted relationships. While it is not altogether clear from the available information, it might be expected that a higher lag time in the headwaters could be related in part to a lower antecedent soil moisture content, so that more time is needed to generate a runoff response. This is consistent with the difference between Event 1 (coefficient 91 and high antecedent streamflow levels (Figure 2)) and Event 2a (coefficient 129 and low antecedent streamflow levels (Figure 3)). However, it is inconsistent with Event 2a having a high coefficient (129) while Event 5 (with a presumed low antecedent moisture content) has a coefficient of only 95. This emphasises again the importance of rainfall location relative to the catchment outlet when considering localised (convective) events. The fitted coefficients for the other events (i.e., Event 2b, 3, 4, 5) show very similar values. Rainstorm structure and catchment antecedent conditions therefore dictate the lag time of a flood. Given the variations in lag time that can be produced, it may be misleading to derive a single general relationship in an attempt to characterise a catchment.

Catchment flood peak scaling

The relationship between peak discharge and catchment area is examined for the six largest events (1–6) between 2003 and 2007 (Figure 10). The analysis includes two additional extreme flood events which occurred on 20th November 2009 (Event A) and 6th December 2015 (Event B). The latter flood caused widespread flooding similar to Event 3. These two floods occurred outside the CHASM monitoring period when the full network was active and as a result the smaller catchment scales are not represented for Event B. However, the Gais Gill station was still active during Event A. Nevertheless, the data from these extreme flood events can be compared against the CHASM network data (and in particular Event 3) to test the hypothesis that there is a common relationship for extreme floods.

To explore the relative influence of storm type and antecedent condition, Figure 10 (top) explores the relationship between peak discharge and catchment area for (a) all the data (Figure 10; top left), (b) grouping peak flow data by antecedent moisture conditions (Figure 10; top centre), and (c) grouping peak flow events by storm event type (convective or synoptic) (Figure 10; top right). When all events are plotted the resulting exponent is 0.79. Events which



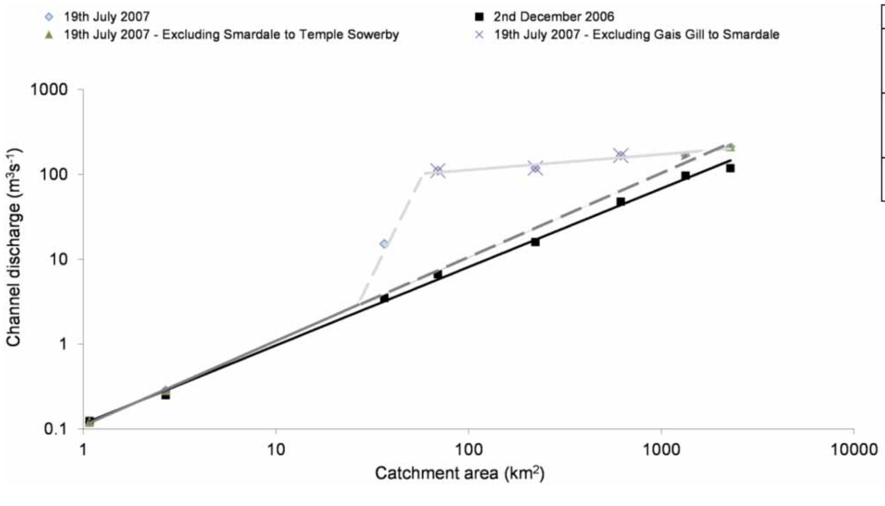
Event		k	r^2
26/12/2003	1	0.75	0.99
31/01/2004	2a	0.72	0.98
02/02/2004	2b	0.74	0.99
07/01/2005	3	0.86	0.99
11/12/2006	4	0.72	1.00
10/08/2004	5	0.68	1.00
19/07/2007	6	1.06	0.93
19/07/2007 inc. KS	6a	1.03	0.84
20/11/2009	A	0.87	0.98
05/12/2015	B	0.64	0.90

Figure 10 | Power regression models for: [Top] relationship between peak discharge and catchment area for all data grouped together (top left), grouping peak flow data by antecedent moisture conditions (top centre), and grouping peak flow events by storm event type [synoptic/convective] (top right). [Bottom] Flood peak discharge as a function of rainfall event and catchment area for individual events; Event 6 models are fitted to data within the nested system only [grey full line] and including the Kirkby Stephen data from outside the nested system [grey dashed line].

commence with a low antecedent condition have a lower exponent (0.75) compared to those events which begin with higher antecedent conditions (0.81). Finally, there is little difference in the exponent value when grouping convective events (0.78) and synoptic scale events (0.79). The results from Figure 10 (top) show that changing from dry to wet increases the flood peak law exponent, while changing from synoptic to convectional lowers the coefficient, at least for the events studied here. A statistical t-test shows that there is no significant difference statistically in the slopes of the power laws for all groupings (wet vs dry and convective vs synoptic) ($p > 0.05$). Nevertheless, there appears to be a trend of increasing exponent in the power law for bigger storms, highlighting the need to explore the exponents of each storm individually.

Given that peak runoff is simply peak discharge normalised by area, the area scaling of peak discharge is the inverse of the runoff scaling. The resulting individual storm patterns are therefore explained in the same way as for the runoff and the scaling relationship exponents are closely related. The peak discharge scaling is presented, however, as it provides a different context, it allows direct comparison with previous studies (e.g., related to Equation (1)) and it enables comparison with the two post-CHASM events. Thus the four moderate winter events (excluding Event 3) show considerable uniformity, with fitted power law exponents in the range 0.72–0.75. The relatively high exponent (0.86) for Event 3, indicating a more rapid rate of downstream increase in peak discharge, is thought to reflect the greater spatial extent of heavy rainfall, whereby the lowland parts of the catchment contribute significantly to the discharge, plus major inputs from Lake District rivers joining below Temple Sowerby. By contrast, the summer event (Event 5) has a relatively low exponent (0.68), i.e., a lower rate of downstream increase in peak discharge, corresponding to the more patchy spatial input of rainfall and perhaps also to a lower effective rainfall arising from the higher soil moisture deficits of the summer period. Figure 10 includes Event 6; the short lasting, more localised event (grey line) plotted with two different power law models. The first model (solid grey line) shows the flood peak scaling within the Gais Gill–Smardale nested catchment system and does not include the Kirkby Stephen catchment in which the rain fell. The model fit is good ($R^2 = 0.935$). When Kirkby Stephen is added (Figure 10, dashed grey line), though, there is clearly a disconnection between this station and the rest of the sites. As in Figure 8 this reflects the localised nature of the storm and the resulting rapid attenuation of the flood wave downstream. The two extreme floods that occurred outside the main CHASM monitoring period have fitted power law exponents of 0.87 (Event A) and 0.64 (Event B). Figure 10 indicates that the flood peak values of Event B were similar to those of Event 3 and Event A was the third largest recorded since 2003. Therefore, it would be expected that the exponent of Event B should be similar to that of Event 3 rather than that of Event 5. In fact, the coefficient of 0.64 is derived for a limited range of areas (less than one log cycle) compared with Events A and 3 (which included the headwater catchments). In detail, the data for Event B are quite consistent with the other two events and the low coefficient therefore simply demonstrates the error that may occur if the database does not cover a sufficient range of scales. The overall conclusion is that the relationships for the three extreme floods (Events 3, A and B) do have a similar coefficient of around 0.86, thus supporting the hypothesis of a common relationship.

Figure 11 compares the Event 6 peak discharge data with a winter baseflow pattern (2nd December 2006), which is selected to show a well-defined power law for discharge increasing with area. In particular, the pattern was selected for the similarity of its headwater discharges (Gais Gill and Artlegarth) and relative similarity of its most downstream discharges (Great Corby and Sheepmount) with those of Event 6. Fitting a model that links Event 6 data for these four sites yields a power law that is similar to the winter baseflow relationship and that can be used as a base line for analysing the response to Event 6 (Figure 11, dark grey line). The base line represents the spatial variation in base flow for the Eden catchment. The rainfall was localised in the Kirkby Stephen catchment and the top line (light grey line) therefore shows the downstream variation in peak discharge for the nested sequence beginning with the Kirkby Stephen station, which is common with the main instrumented nested sequence from Great Musgrave (222.5 km^2) downstream. The downstream rate of increase in peak discharge is much smaller (exponent = 0.184) than the base



	k	r^2
Event 6 ex GG to SM	**0.18**	0.85
Event 6 ex SMA to TS	**1.00**	0.99
02/12/06 base line	**0.92**	1.00

Figure 11 | Comparison of Event 6 with similar flow scaling at Gais Gill, Artlegarth, Great Corby and Sheepmount to baseflow on 2nd December 2006.

line rate (0.996) (and indeed the rate for the winter storms' peak discharges), indicating the rapid attenuation of the flood wave. The Smardale catchment (36.6 km^2), within the main nested sequence, was slightly affected by the rainfall and its peak discharge therefore lies above the base line relationship. The localised event in the Kirkby Stephen catchment thus creates a 'hump' on the baseline scaling relationship. Localised events can therefore distort the general flood peak scaling pattern by causing a shift in the exponent value of the fitted model.

DISCUSSION

The significance of the results derives from the unusual detail of the data on which they are based. In particular, this detail enables the spatial and temporal runoff response to be analysed as a function of the spatial and temporal pattern of the rainfall, across a four orders of magnitude variation in catchment area and incorporating catchment characteristics and seasonal differences. The study was limited to six large events during the study period. While this may have limited the statistical validity of the analysis, the study considers storm events which both partially and fully covered the catchment (so avoiding the limitation within the large scale study by Ayalew *et al.* (2015)) and covers a good range in terms of magnitude; all the selected events resulted in some level of flooding within the catchment (ranging from localised to widespread flooding). Therefore, the results can be related to implications for flood risk management. It also demonstrates the importance of monitoring flood peaks across multiple scales to ensure an accurate evaluation of the area-dependency relationships, so providing a close insight into catchment response and enabling headwater response to be linked with the response at the larger catchment scale.

The major distinction between the measured events is their seasonal nature. The winter events correspond to the classic UK pattern. Frontal rainfall occurs across the whole of the catchment but is higher in the headwater areas, which are therefore the prime source of runoff. Flood waves develop in the headwaters and progress downstream. The flood peak increases as the contributing area increases but at a lesser rate than the area itself. Peak specific runoff therefore decreases in the downstream direction. For all events, the peak runoff is more or less constant with area up to 20–30 km^2. At larger areas, which are increasingly lowland in nature, the downstream rate of decrease in peak runoff is highest (and the rate of increase in peak discharge is lowest) for events in which rainfall is concentrated in the headwaters, while the opposite occurs when the heavier rain falls also in the lowlands. Overall, though, the downstream rate of increase in peak discharge varies over characteristic ranges and values of the exponent k in Equation (1) of around 0.75 and 0.86 can be considered representative of the Eden for moderate to large and extreme floods, respectively. The biggest events appear to involve (relatively speaking) the most uniform rainfall, with high inputs in the lowland as well as the upland areas. The apparent increase in exponent with severity of flood is therefore consistent with the expectation of a linear relationship (exponent = 1) for the most extreme case of a constant uniform rainfall producing, eventually, uniform runoff equal to rainfall across the entire catchment. Lag times increase in the downstream direction but the rate of increase, and the lag time for the headwater catchment, vary with rainfall pattern and antecedent moisture content. The variation is too high for a single relationship to be considered representative of the catchment for all events.

By contrast, the summer convective events display a more erratic behaviour and the flood response depends on the location of the rainfall. Event 5, although consisting of localised storms, nevertheless occurred across much of the catchment. It therefore produced spatial variations similar to those of the winter events, albeit with a lower downstream rate of increase in peak discharge. Event 6 was more localised and the response was therefore disconnected from the upper part of the instrumented nested catchment sequence.

Figure 11 (comparing Event 6 peak discharge data with a winter baseflow) can be generalised into two simple models of flood peak and base flow scaling (Figure 12(a)). For a large synoptic scale storm, affecting the whole of the catchment, flood peak discharge increases more or less uniformly with area across all areas, following a power law relationship (Figure 12(a)). Possibly the exponent is higher for the headwater area than for the lowland areas, but a single exponent allows a reasonable representation of the full catchment. Base flow follows a similar scaling relationship, with a lower coefficient and possibly with an

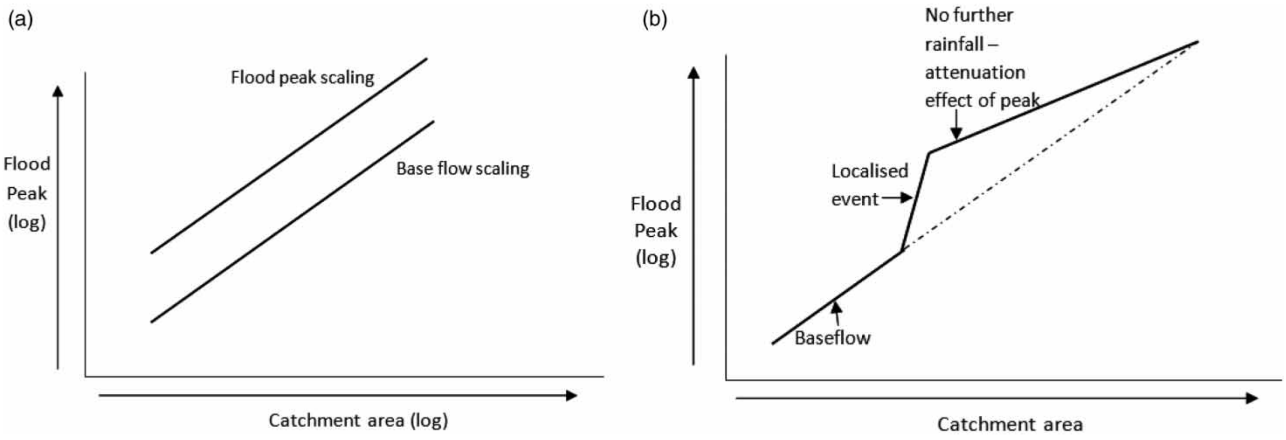


Figure 12 | (a) Scaling trends for flood peak and base flow for a hypothetical catchment and (b) the effect of a localised storm in a sub-catchment creating a hump on the base flow scaling law.

exponent closer to unity (Figure 12(a)). However, if only part of the catchment is affected by rainfall (e.g., an event affecting the upper but not the lower catchment), the peak discharge would be comparable with the magnitudes from the flood peak relationship of Figure 12(a) in the upper catchment, but would then attenuate rapidly downstream, eventually falling to the level of the base flow. Depending on the location of the rain storm, there may also be an upstream rise from base flow to flood magnitudes, creating the hump shown in Figure 12(b). The exact pattern would depend on the scale of storm, the magnitude of the flood peak and the length of the channel network. The exponents will differ greatly in these two models. These findings generally are different from those of Paschalis *et al.* (2014), who proposed that the flood response is strongly affected by the temporal correlation of rainfall and to a lesser extent by its spatial variability, and built upon the research of Ayalew *et al.* (2015) which omitted storm events that partially cover a catchment. However, while the scale of the catchment study here is similar to that in the Kleine Emme river basin (see Paschalis *et al.* 2014), the precipitation network in the Eden is almost four times as dense (although Paschalis *et al.* did combine point measurement with radar data and Ayalew *et al.* used radar data solely). The dense raingauge network in the Eden highlights the importance of the spatial variability of a storm on the resulting flood peak. However, both studies found that initial soil moisture conditions play a paramount role in mediating the response.

CONCLUSIONS

The dense hydrometric network of the upper Eden catchment has allowed an unusually detailed study of the relationship between rainfall spatial variability and flood response as a function of catchment scale across four orders of magnitude of area (1–1,000 km^2) and for a range of storm events.

1. Detailed rainfall maps contrast the patterns of synoptic winter storms and convective summer storms.
2. For the winter events, flood peak discharge increases in the downstream direction but at a lesser rate than catchment area. Consequently, peak runoff decreases downstream. Extreme events appear to conform to a common scaling law. Lag times increase in the downstream direction as a function of rainfall pattern and antecedent moisture content but are not convincingly represented by a single relationship.
3. The flood response to the convective storms depends on the location of the rainfall and the downstream rates of change of runoff and peak discharge can vary significantly from the winter storm relationships. In particular, a localised event producing a flood peak that attenuates rapidly downstream can create a hump in the relationship relative to the uniform catchment-wide scale dependencies of the winter events. Lag times are a function of where the rain falls relative to the catchment outlet.

The study adds a detailed data set to the limited information on spatial variation in single event peak flow, identified in the Introduction. The results link the flood response to the rainfall spatial distribution, thus addressing the question raised by Bell & Moore (2000). They clearly identify the principal runoff-generating regions and show how the runoff is transmitted downstream. Particularly for large synoptic storms, characteristic scaling laws for peak discharge have been quantified, illustrating the non-linear nature of the cross-scale variations but highlighting the importance of representing all orders of area magnitude within a catchment in the scaling law. Such laws provide a means of linking the headwater catchments in which research has typically been carried out with the larger scale at which planners and decision-makers operate (Geris 2012; Ewen *et al.* 2015). Future research could investigate in more detail the apparent absence of scaling effect in the headwater catchments (area 20–30 km^2) and the generality of the findings for the UK could be investigated in other catchments. Extension of the findings to larger spatial scales (10,000 km^2 and larger) requires studies of continental scale rivers (e.g., Ayalew *et al.* (2015) for the Iowa river basin, USA) and there is an additional need to explore scale dependencies in different climatological regions. Long-term studies would allow a full range of flood events, including extremes, to be incorporated.

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