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Characterising flash flood response to intense rainfall and impacts using historical information and gauged data in Britain

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Flash flood; historical data; intense rainfall; pluvial flood; rate of rise; wall of water; wavefront steepening.

Abstract

We analyse chronologies of historical flash floods derived from searches of newspaper archives and other sources commencing before 1800 and recent gauged rainfall and stream flow data. Five key examples are chosen to illustrate specific features of flash floods. Pluvial flash floods arise from rainfall before it reaches a watercourse and may cause severe flooding of land and properties far from rivers. River flash floods, like pluvial floods, have the characteristic of rapid speed of response, a principal source of risk to life. Intense rainfall can generate 'walls of water' in river courses which can propagate long distances downstream and steepen, without upstream structural failure. Steeply rising wavefronts more commonly occur on steep upland catchments but, where intensities of extreme short period rainfall are sufficient, such wavefronts can also occur on lowland catchments. A definition of flash floods from intense rainfall, relevant to British landscape and climate, is proposed.

Introduction

Interest in flash floods has been stimulated in Britain by the occurrence, in the last decade, of events of unusual severity caused by short period intense rainfall on small catchments. Particularly notable were the flood on the River Rye at Helmsley[1] in North Yorkshire in 2005 (Wass *et al.*, 2008) and at Boscastle[2] in 2004 (HR Wallingford, 2005) (Figure 1). Both floods caused extensive damage and destruction although no lives were lost. Floods from surface water in the Tyneside area[3] in 2012 (popularly known as the 'Toon Monsoon') were similarly beyond the experience of residents, and short period rainfall totals were estimated at > 100 years return period (Environment Agency, 2012), with major disruptions of road, rail and metro networks at rush hour. The Pitt Review (Cabinet Office, 2008), which analysed the nature and consequences of the 2007 Midland floods, noted that some two thirds of affected properties were flooded by pluvial flooding and that such pluvial flood risks lacked the attention given to flooding from rivers.

Flash floods, whether from surface water or from the overflow of rivers, infrequently occur at any one location but such events occur somewhere in the UK multiple times within a decade. Events may pass virtually unnoticed in upland catchments yet have major but localised impacts through erosion and transformation of river channels, e.g. on the Thinhope Burn[4] (Milan, 2012). However, historical floods in cities, towns or villages have caused multiple fatalities. These include the 1952 Lynmouth[5] flood in North Devon in which 34 people died and 420 were made homeless (Dobbie and Wolf, 1953), and the 1920 flood on the Lud at Louth[6] (Clark and Arellano, 2004) which killed 23 people (in 20 min) and made 1000 homeless. Indeed, Barredo (2007) notes that flash flooding caused 40% of the flood-related casualties in Europe during 1950–2006.

Given the severity of such events, it is perhaps surprising that limited attention has been given to the characteristics of flash flood generation and transmission in the UK beyond the description of individual events. Although Hand *et al.* (2004) categorised extreme rainfall as a basis for causing flash floods, they did not investigate the river and surface water flood response. Additionally, Acreman (1989) examined extreme historical floods in terms of peak levels and discharges. However, the two characteristic features of flash floods which are the principal sources of risk to life, rapidity of onset and rate of rise in level, have not been previously studied.

Numerous studies have also been made of individual flash floods in southern Europe, mainly defined by extreme rainfall totals and peak discharges (e.g. Huet *et al.*, 2003; Lefrou

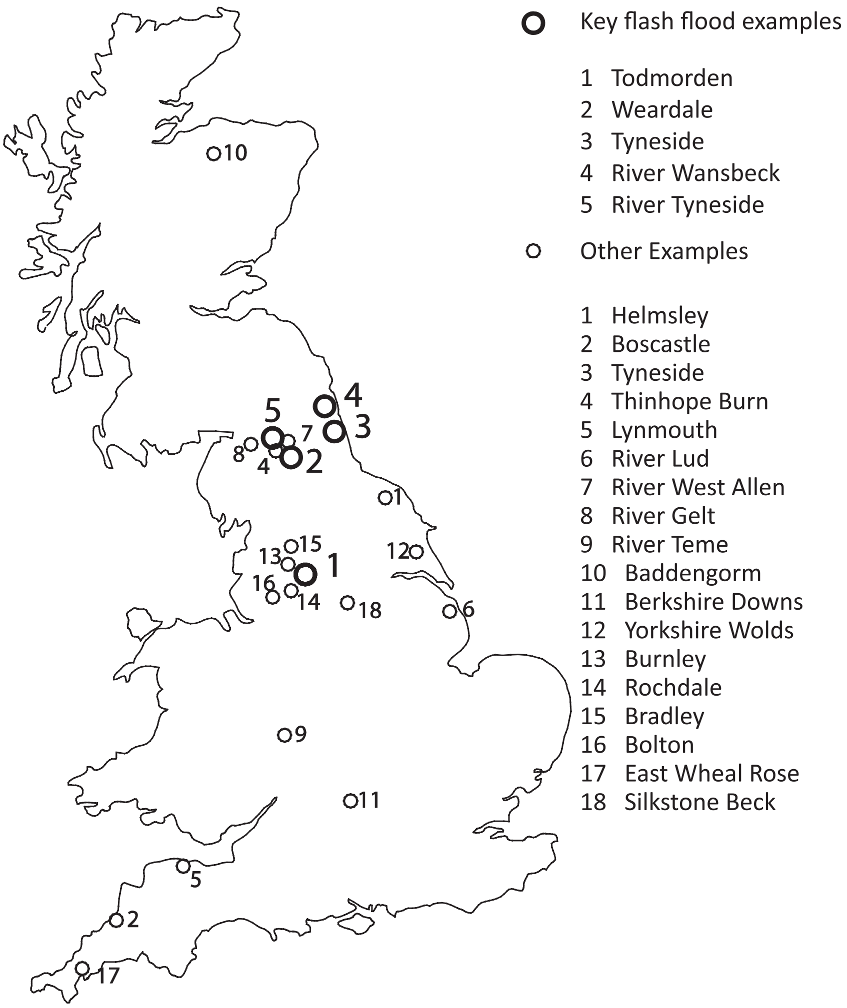

Figure 1 Map of Britain showing location of flash floods mentioned and superscripted in the text.

et al., 2000). Gaume *et al.* (2009) compiled an inventory of 550 extreme flash floods in seven countries in Europe; Britain was not included. Events were defined in terms of peak discharge with rainfall duration < 24 h and on catchments generally < 500 km^2, not speed of onset, so it is not clear how the selected events differed categorically from large 'normal' floods. Douvinet and Delahaye (2010) described flash floods (*crues rapides*) on the plateaus of north-western France in a landscape and climate similar to southeast England, with many of the 269 compiled events occurring in dry valleys, and specifically refer to the speed of onset of flooding.

The UK Natural Environment Research Council-funded Flooding from Intense Rainfall (FFIR) programme was initiated in 2013 and two large multi-institutional projects funded. The SINATRA (Susceptibility of catchments to INTense RAinfall and flooding) and FRANC (Forecasting Rainfall exploiting new data Assimilation techniques and Novel observations of Convection) projects will address such issues as improvements in meteorological forecasting, understanding flood response and impacts of flooding from intense rainfall. In this paper, we examine the characteristics of historical and recent flash floods in an attempt to draw general conclusions on the meteorological conditions under which flash floods are generated, the speed of onset of the flood, variations in catchment vulnerability and the risks to life associated with such events. This study is designed to demonstrate those characteristics of flash floods (or floods from intense rainfall) that differ from 'normal' floods as a basis for testing new model formulations and to select catchments and events for modelling within the SINATRA project. There is no intention here to model any of the events in detail. Assessment of flash flood characteristics is restricted to events arising from intense short period rainfall rather than from failure of dams or embankments. A definition of flash floods from intense rainfall, relevant to British landscape and climate, is also proposed.

Data and methods

The analysis is based on previous historical chronologies of river floods prepared for the Environment Agency by JBA Consulting and by archives from Archer (1992). This was supplemented with respect to flash floods by a comprehensive search of the British Newspaper Archive (BNA) (www.britishnewspaperarchive.co.uk) for events in northeast, northwest and southwest England and for selected extreme events elsewhere in England that illustrate specific features of flash floods. BNA has few archived records after 1950, and more recent years have been investigated using library sources of hardcopy or microfilm of newspapers and by examination of gauged rainfall and stream flow records.

Flash flood examples

Five events have been selected to illustrate typical characteristics and severities of flash floods with reference to location, extent, pathways, run-off response and impacts. Features from these examples are then combined with information from other events to generalise flash flood characteristics.

- 9 July 1870; Todmorden
- 17 July 1983; Upper Weardale
- 28 June 2012; Tyneside
- 3 August 1994; River Wansbeck
- 30 July 2002; River Tyne

9 July 1870; Todmorden

The upper Yorkshire Calder is a narrow and steep sided valley fed by 'cloughs' from the surrounding moorland (Figure 2). The valley floor is heavily populated and traditionally occupied by cotton mills and homes for the workers. On 9 July 1870, observers of the thunderstorm at Todmorden and the upper Calder valley saw the build up of the storm clouds over the headwater moors between the Calder and Irwell catchments. The storm in mid-afternoon lasted about an hour, although at Todmorden it rained for only 15 min, and at nearby surrounding areas it remained completely dry (British Rainfall, 1870; Sedgwick, 1870).

An observer writing from Cornholme, 3 km upstream from Todmorden, noted the rapid initiation of the flood from low water to a roaring torrent in < 15 min, not only in the river channel but over the turnpike road 30 ft wide by 3 ft deep and carrying entire trees. 'Such was the rapid rise of the water that the carters had to loose their horses from their carts and make for their life, some of the carts being carried away by the flood' (British Rainfall, 1870, p. 103).

In the upper Calder valley, roads were swept away and the bed of the river almost blocked with debris, cotton mills and houses flooded and several of them destroyed. A number of deaths occurred, including a man crossing a bridge to escape the flood at its onset with his two children lost from his grip and washed away by flood. At Todmorden itself, the flood brought rapid destruction washing away walls, bridge parapets and flooding tenements up to nearly 2 m.

There were no rain gauge measurements but one container registered 3.5 inches (89 mm) while other estimates of the storm total varied from 4 to 9 inches (102 to 229 mm) over the moor (British Rainfall, 1870).

Todmorden has been the scene of frequent flooding over the last 150 years, both from intense thunderstorms and

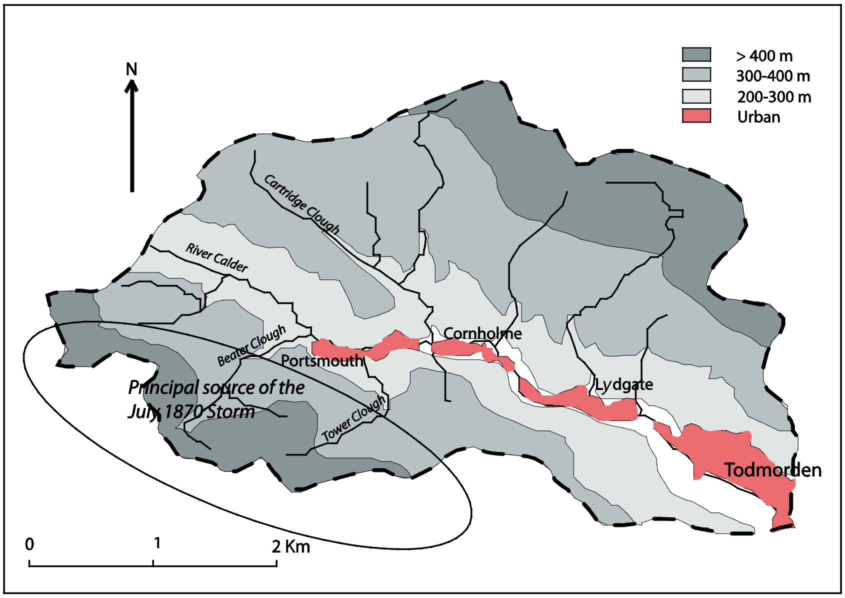

Figure 2 The Upper Calder catchment to Todmorden showing the principal 'cloughs' (steep valleys) contributing to the flood of July 1870 and the extensive urbanisation of the valley floor.

more prolonged rainfall. The most recent flood on 30 July 2013 was again caused by a severe thunderstorm, lasting for less than an hour.

17 July 1983; Upper Weardale

Similar with the event in the Upper Calder, the storm in Weardale was most intense on the catchment boundary, in this case between the Wear and the Tees catchments. A separate but concurrent storm cell occurred over the headwaters of the river Allen, a tributary of the Tyne. The nearest rain gauge to the storm centre at Ireshopeburn Farm (Figure 3) recorded 104.8 mm between 15:30 and 18:00 with a core period from 15:45 and 17:00 (1.25 h), and the storm seemed even more intense over the high moors to the south.

Evidence of the storm was most clearly seen in the occurrence of five peat slides, three draining into the Ireshope Burn, one into the West Grain Beck and one into the Langdon Beck catchment, a tributary to the River Tees (Carling, 1986a,b). The two largest slides completely evacuated peat from the underlying soil, leaving it grooved and bare (Figure 4a) over areas of more than 2.5 hectares and carried it up to 500 m downslope (Figure 4b).

The storm also generated exceptional flood flows and associated bed load and suspended sediment transport. The most remarkable was on West Grain Beck where the flood wave overtopped the recorder house and removed its slate roof, destroying the recorder (Archer, 1992, 1994). A short distance downstream, with a catchment area of 1.86 km^2, Carling (1986a) estimated the peak flow at 22 m^3/s based on culvert geometry and 16 m^3/s on the basis of the size of boulders transported; the largest was more than a meter in diameter (Figure 4c). On the Langdon Beck, the transported material was mainly peat, including large blocks (Figure 4d).

Downstream, peak flow was not remarkable but the rate of rise was the largest in more than 20 years of record, as shown in Table 1. Notably, at the West Allen[7] the entire rising limb of the hydrograph to more than median annual maximum (QMED) occurred within 15 min, and a young man swimming in the river near the gauging station narrowly escaped drowning by grasping an overhanging tree (Archer, 1992). On the Ireshope Burn near its confluence with the River Wear the flood wave picked up an occupied caravan and hurled it against a wall, which fortunately held it in place until the flood receded. Another unoccupied caravan was carried off into the River Wear. Unlike the Upper Calder, the

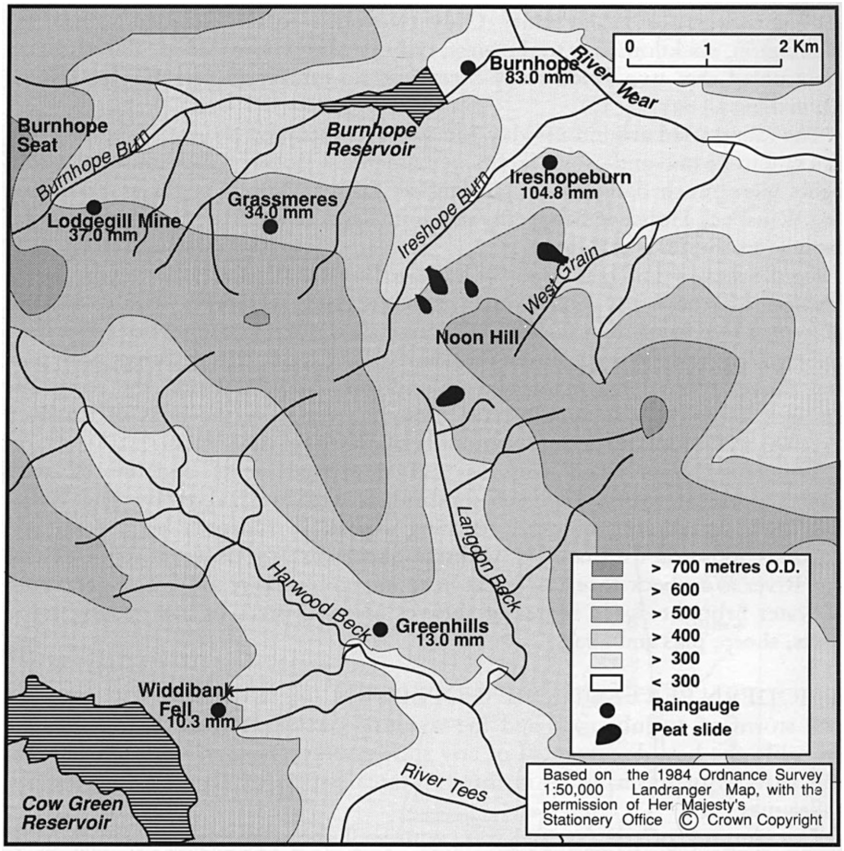

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Figure 3 Storm rainfall and peat slides in Upper Weardale and Teesdale on 17 July 1983 (after Archer, 1992).

Figure 4 (a) Evacuation zone of a peat slide on Noon Hill, photographed the following winter; (b) Track of the peat slide with rolled spindles and blocks; (c) Gauging station on the West Grain Beck with boulder jam; and (d) Flood flow on the Langdon Beck laden with peat blocks.

Table 1 Flow and level statistics for the Upper Weardale flash flood on 17 July, 1983

River	Station	Catchment area (km^2)	Peak flow (m^3/s)	Median annual flood (m^3/s)	Maximum 15-min level rise (m)	Total rise in level (m)
Wear	Stanhope	171.9	94	119.0	1.54	1.83
Wear	Witton Park	455.0	77	203.4	1.30	1.66
West Allen	Hindley Wrae	75.1	67	53.1	1.51	1.51

Weardale headwater valleys have no permanent habitation, and the capacity of the receiving Wear channel was sufficient to hold the flood inbank. Although there were no further reported incidents, the rate of rise statistics show the potential risks to downstream river users.

28 June 2012; Tyneside

This flash flood event on the 28 June 2012 in the city of Newcastle upon Tyne and the surrounding areas, locally known as the 'Toon Monsoon', provides a good example of a pluvial flood. This was caused by a series of intense thunderstorms which crossed England during the 28th of June 2012 associated with a series of cold fronts. The thunderstorms also affected other parts of the UK such as the Midlands and were caused by a tongue of moist air extending from the Tropics – often called a 'Spanish Plume' or 'Atmospheric River' (Lavers *et al.*, 2013). The event in Newcastle started at about 16:30 at the height of the evening rush hour and lasted for ~ 2 h, during which ~ 50 mm of rain fell; equivalent to the expected total rainfall for June. A similar event on the 5 August saw 40 mm rain fall in just an hour and a half.

The 28 June 2012 event caused serious flooding, widespread damage and travel chaos. Traffic was gridlocked in the city centre, with many other road closures in the region. Drivers were forced to abandon their cars, with many commuters stranded due to public transport closures. Northern Powergrid reported that 23 000 properties were left without electricity. In Newcastle around 500 properties suffered internal flooding and other gardens, driveways or garages were flooded, with flood waters typically at the level of air bricks; 66% of properties were flooded for the first time (Newcastle City Council, 2013), mainly within an hour of the start of the rainfall event.

With respect to peak flows on urban tributaries, the River Team, south of Newcastle reached its highest level in a 22-year record. Peak flow on the Ouse Burn draining the north and west of Newcastle was third highest in a 28-year record but with an exceptional rate of rise of 1 m in 30 m at Crag Hall on the lower Ouse Burn, significantly greater than in any previous event with steepening as the wavefront moved downstream (Environment Agency, 2012). However, no properties were flooded as the result of overflow of the Ouse Burn; all properties were flooded from surface water.

This event was not unprecedented. Newcastle upon Tyne has received many heavy thunderstorm-like events causing flash flooding in the past – with four events probably greater than the 2012 event affecting the city centre since 1800. Two events in the last century were clearly larger than that of 2012 on the basis of both rainfall and flood impact. On 16 Sep 1913, 2.85 inches (72 mm) of rain fell in 1 h and 30 min; 'Flooding occurred at numerous points in the city, miniature lakes two feet deep being formed in different thoroughfares. A torrent of water swept through St Thomas churchyard, burst through the floors and windows of Lovaine Hall and flooded it to a depth of 4 feet . . .' An even larger flood occurred on 22 June 1941 when 1.97 inches (50 mm) was recorded in 35 min and 3.74 inches (95 mm) in 85 min.

Until the 17th century, the centre of Newcastle was drained by a series of steep sided natural channels flowing southward to the Tyne. Gradually these were culverted and filled in to form a series of depressions blocked by buildings and dependent on adequacy of subsurface drainage. However, with intense rainstorms ancient river channels may be reactivated, and ponding occurs where culvert capacities are exceeded. Some localities show evidence of repeated flooding over more than 150 years, e.g. Newgate Street, flooded to a depth of ~ 1.3 m in 2012 and flooded from less intense rainfall in September 1995 and July 1997. Shops and houses were reported flooded in the same location as early as 1833 and several times in 1846, leading to a petition from residents to the City Mayor for improvements to be made to the sewerage system. The problem of hidden rivers is not unique to Newcastle, and other cities show evidence of serious surface water flooding where culvert capacities of hidden rivers are inadequate.

3 August 1994; River Wansbeck

A very dry summer from May to July 1994 was followed on the Wansbeck catchment in northeast England by an exceptional thunderstorm with daily rainfall of > 70 mm at nine stations. However, a 15-min total of 30 mm at 15.15 recorded at Wallington Hall was even more exceptional (Archer, 1994).

A gauging station on the Hart Burn, one of three major tributaries of the river Wansbeck, showed a 15-min rise in level of 1.32 m at 19.00. At Mitford (catchment area 287.3 km^2), downstream from the confluence of the three major tributaries, the 15-min rise was 1.26 m, with an equivalent increase in discharge from 0.6 m^3/s to 44.5 m^3/s at 20.45 (Figure 5a). Thus, the lag from rainfall to peak runoff at Mitford in this event was only 5.5 h compared to average lag times of more than 9 h. With a further half hour travel time to the town of Morpeth on the Wansbeck, the flood wave arrived at dusk with riverside activity (including crossing stepping stones) at a low level; there were no reported incidents. Had it arrived a few hours earlier, the rapid onset of flooding had the potential for a serious risk of drowning. A plot of the annual maximum 15-min and hourly rates of

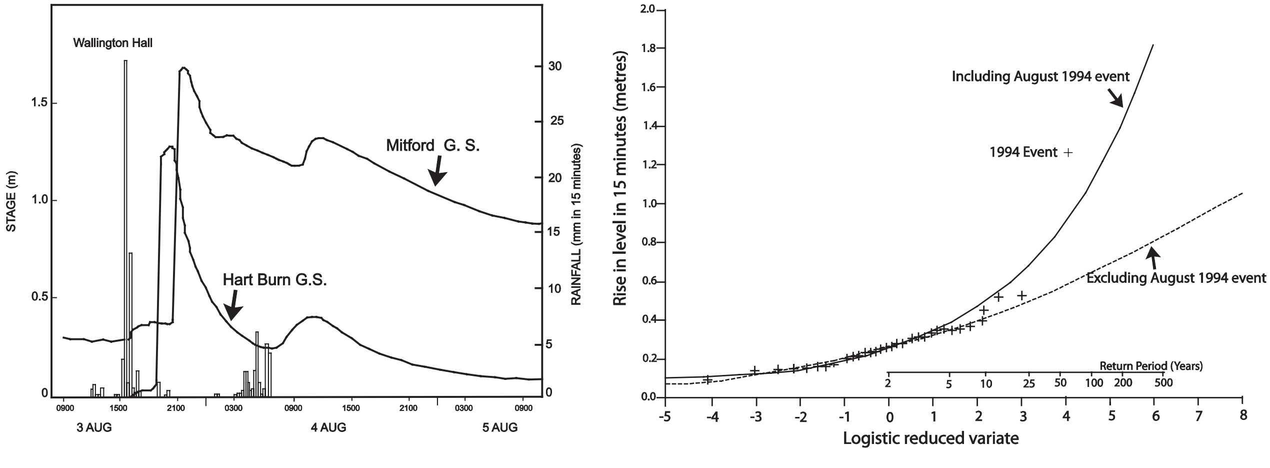

Figure 5 River Wansbeck showing (a) level hydrographs on the Hartburn tributary and at Mitford for event of 3 August 1994 and (b) frequency distribution of 15-min annual maximum rise in level 1979 to 2012 at Mitford including and excluding the August 1994 event.

rise for the Wansbeck at Mitford show that the 1994 event is an outlier in the series, and more than double the previously experienced rate of rise (Figure 5b). Unlike the previous examples, the river Wansbeck is a lowland agricultural catchment with a highest elevation of 330 m and a channel slope of less than 4 m/km.

30 July 2002; River Tyne

The configuration of the River Tyne catchment is shown in Figure 6. Localised extreme rainfall occurred in the upper reaches of the South Tyne on 30 July 2002. The one recording rain gauge adjacent to the catchment recorded 26.2 mm in the first 15 min of the storm followed by a quiescent period but with total storm rainfall of 79.6 mm over a 10.5-h period. This generated an extreme flood at Alston gauging station and a downstream flood wave with exceptional rates of rise which persisted to the tidal limit (Figure 7).

The rate of rise in level (meters) and flow (m^3/s) was extracted for durations of up to 1 h for four gauging stations on the South Tyne and Tyne (Table 2).

The following observations are made from this analysis:

1. The peak flow at Alston (118 km^2) was the rank 1 flood in a 30-year record. While the magnitude of peak flow remained about the same down to the lowest gauging station at Bywell (2175 km^2), the flood peak rarity diminished downstream and nowhere was even the annual maximum. At Featherstone, it was equivalent to a 5-year return period flood but at Haydon Bridge the peak was only 0.72 of QMED and at Bywell only 0.42 of QMED.
2. In contrast, the steep wavefront was maintained to the Tyne estuary with notable 15-min increases in level of 1.22 m at Featherstone and 1.33 m at Bywell – the highest observed in the record. Fifteen-minute discharge increases of over 150 m^3/s were observed at Featherstone, Haydon Bridge and Bywell.
3. At Ovingham, 2 km upstream from the tidal limit at Wylam, it was estimated from visual cues that water level rose 1 m in 9 min.

Although there were no reported flood incidents, such a rapid rate of rise poses a significant threat to life. The Tyne is noted as the best salmon fishing river in England and fishermen often stand knee-deep in the river to cast into the deepest water. A rise of over 150 m^3/s in 15 min implies a rise of at least 10 m^3/s or 0.10 m in level in 1 min. In such conditions, a fisherman would have to escape from the water in less than 1 min to avoid being swept away.

Discussion

Meteorological origins

The examples illustrate key characteristics in the origin and development of flash floods in Britain. Extreme rainfall associated with flash floods is convective and may result from

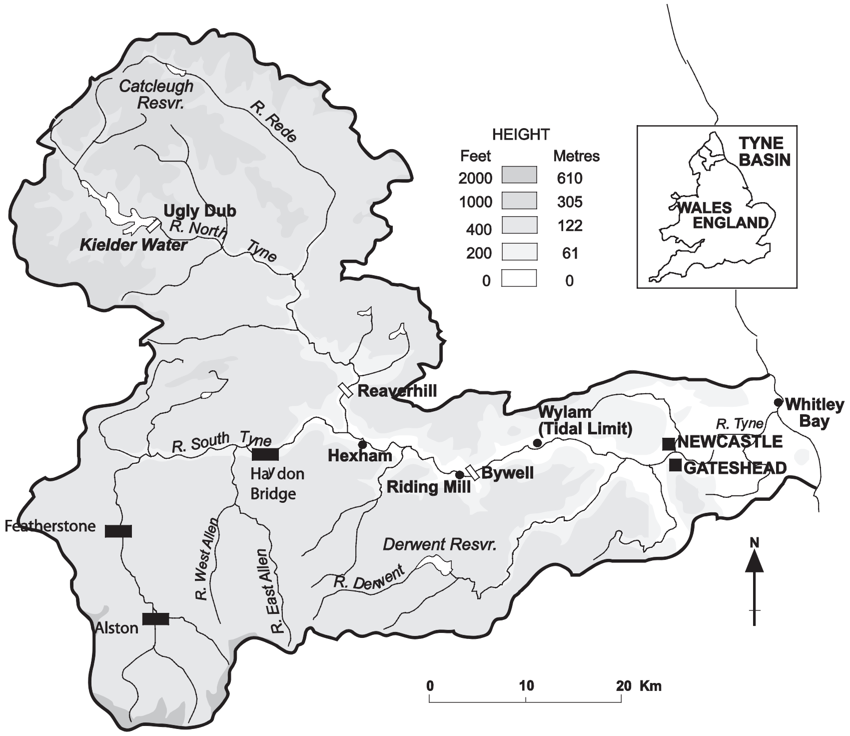

Figure 6 The River Tyne catchment showing gauging stations used in this analysis.

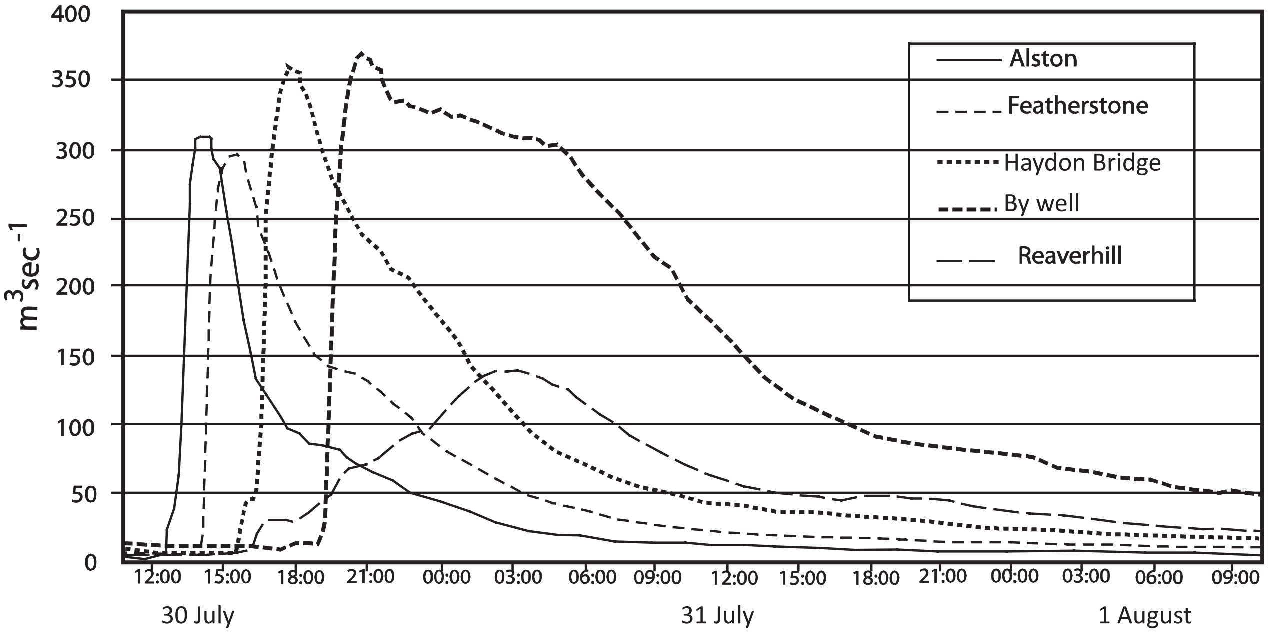

Figure 7 Progress of the flood wave down the South Tyne and main Tyne at Alston, Featherstone, Haydon Bridge, Bywell and Reaverhill (North Tyne).

Table 2 Maximum rates of rise in flow and level for 15-, 30- and 60-min periods and peak flow and associated return periods for four stations on the rivers South Tyne and Tyne

Station Catchment area	15-min max rise in Q and H (m^3/s and m)	Start time of max rise	30-min max rise in Q and H (m^3/s and m)	Start time of max rise	1-h max rise in Q and H (m^3/s and m)	Start time of max rise	Peak flow (m^3/s) time
Alston	116.9	13.00	229.3	13.00	272.5	12.45	310.7
118.0 km^2	0.748		1.220		2.110		14.00
Featherstone	165.7	14.00	240.7	14.00	283.1	14.00	293.5
321.9 km^2	1.333		1.634		1.79		15.15
Haydon Br	154.4	16.30	221.1	16.15	296.7	16.15	358.6
751.1 km^2	0.900		1.478		1.831		17.45
Bywell	169.9	19.15	253.5	19.15	327.0	19.15	367.0
2175.6 km^2	1.220		1.684		2.05		20.45

extremely localised individual cells, notably at Todmorden and Weardale, or from mesoscale convective systems (Browning and Hill, 1984). Since it is convective in origin, most flash flooding occurs during the summer months of June, July and August, although events have occurred as late as October. Hand *et al.* (2004) identified over 50% of extreme historical events as being convective in origin, categorising them as either: (1) severe convective events triggered by synoptic scale cold frontal forcing or with large hail; or (2) convective events triggered by mesoscale features.

It is clear that the key factor in flash flood severity and rapidity is neither hail nor total rainfall magnitude but the short period intensity. Observations of 30 mm in 15 min in the Wansbeck catchment and 26.2 mm in 15 min at Alston provide intensity indicators for the generation of flash floods. However, given the spatial variability over short distances in thunderstorm rainfall, it is very unlikely that measured intensities are the maximum occurring over the catchment (Archer and Wheeler, 1991). Given low rain gauge densities, and small spatial extent of convective storm cells, it is likely that floods will often occur where no ground-based rainfall is measured. Reliance must therefore be placed primarily on rainfall radar for assessing observed events. The challenge of improved forecasts of location and magnitude of intense storm rainfall will be met by the FRANC project.

Pluvial floods

Pluvial floods are those which occur between the impact of rainfall (or solid precipitation) at the ground surface and the entry of water to a watercourse. Rainfall, with intensity greater than infiltration capacity, flows over surfaces in sheet flow or develops gullies on friable soils. The surface flow gathers volume and velocity on hill slopes and can gather sufficient momentum to wash away walls and burst in through doorways. In rural areas, flash floods scour fields of soil, stones and crops and carry these with the water into landscape depressions where water may pond to considerable depth. Houses can thus be affected far from rivers, and the water may be heavily laden with sediment and debris. In urban areas, water gains velocity on smooth and impermeable surfaces and may be of sufficient depth and velocity to sweep people from their feet.

Assessing the probability of occurrence of pluvial floods is more problematic than for river floods as there is no single defined channel in which to measure discharge or depth. However a broad assessment can be made on the basis of rainfall amount and of flood impacts, particularly by comparing recent and historical events (e.g. as Archer, 1999; Archer *et al.*, 2007 for fluvial flooding). Rainfall provides a better guide to severity for extreme pluvial events than for river flow since losses are smaller on impermeable urban surfaces and even in rural areas, where infiltration capacity is exceeded. Although pluvial flooding may appear unprecedented, inspection of historical archives may provide additional information. For example, for Newcastle upon Tyne storm rainfall magnitude in 2012 was exceeded by events in 1941 and 1913, and comparison of urban impacts suggests that floods in 1872 and 1839 were also equal or greater than 2012.

Speed of onset

Newspaper and popular reports frequently describe the rise of water level during a flash flood in a river channel as 'a wall of water'. It is difficult to confirm that such descriptions are of a near vertical breaking wave or alternatively of a rapid swelling of the river level over a period of minutes as described for the event of July 2002 on the lower River Tyne (Archer and Fowler, 2014). Gauged information based on river level measurements at 15-min intervals is of no help since a rise in level may have occurred gradually or may have passed as a wall of water. Stilling well lag (Herschy, 1995) may further dampen the gauged rate of rise.

However, given the descriptions of some historical and recent events, we conclude that the rise can be so rapid as to provide a literal 'wall of water' or a breaking wavefront. Archer and Fowler (2014) describe an event in which a 10-year old boy swimming in the River Gelt[8], a tributary of the Irthing/Eden, was swept away and drowned in June 1982 by what was described as a '10 foot wall of water'. Given the narrow width of the channel and the short distance to an escape, the flood front must have been virtually instantaneous. Newspapers also describe a flash flood on the River Teme[9], a lowland tributary of the River Severn below Worcester in September 1852 when 'the water came down the Teme with a "head" similar to the tidal phenomenon on the Severn at the spring and autumn equinoxes' (*Gloucester Journal* 11 September 1852). At least three people were drowned, one when a cottage was swept away.

The need for an upstream structural failure

There is a widespread assumption that an observation of a near vertical wall of water implies the creation of an upstream blockage followed by ponding and failure, e.g. the rapid onset of flooding at Boscastle was assumed to be caused by blockage and failure of an upstream bridge (HR Wallingford, 2005) . The remarks of a railway engineer after a flash flood which destroyed four bridges on the Baddengorm Burn[10], a small tributary of the Dulnain/Spey on 10 July 1923, are revealing (British Rainfall, 1923, p. 50).

> Any eye-witnesses who saw the oncoming avalanche of water indicate that it came in the form of a vertical wall which would certainly imply that it was held up at each successive bridge and came forward as the water from a destroyed dam would come, as the bridges went down one after the other. In 1914 on the other hand, [in a previous flood on the same catchment] I was told by an eye-witness who saw the Baddengorm road bridge carried away, that the flood water approached that bridge in the form of a vertical wall and this although there was no bridge further up the valley to have created a temporary dam.

There is no indication in any of the examples 1, 2, 4, or 5 above that there was any failure of an upstream structure. It is therefore concluded that near vertical rising hydrograph limbs can develop as a response to intense rainfall without the need for blockage and failure of a structure, although a blockage may initiate or enhance such an occurrence.

Downstream steepening of the flood wave

The evidence from example 5 (Tyne, July 2002) indicates that a wavefront can steepen as it moves downstream, and this can persist over a long distance, some 80 km from Alston to the estuary. This behaviour is in contrast to the normal storage attenuation of flood waves in natural channels. At the scale of Figure 7, the steepening is hardly evident but is clearly visible when the change in discharge between successive 15-min observations is plotted against time between Alston and Featherstone and between Haydon Bridge and Bywell (Figure 8).

Similar steepening of the wavefront has been observed on the Tyne in other flash flood events, e.g. July 2007 (Milan, 2012), and for minor increases in flow generated by releases

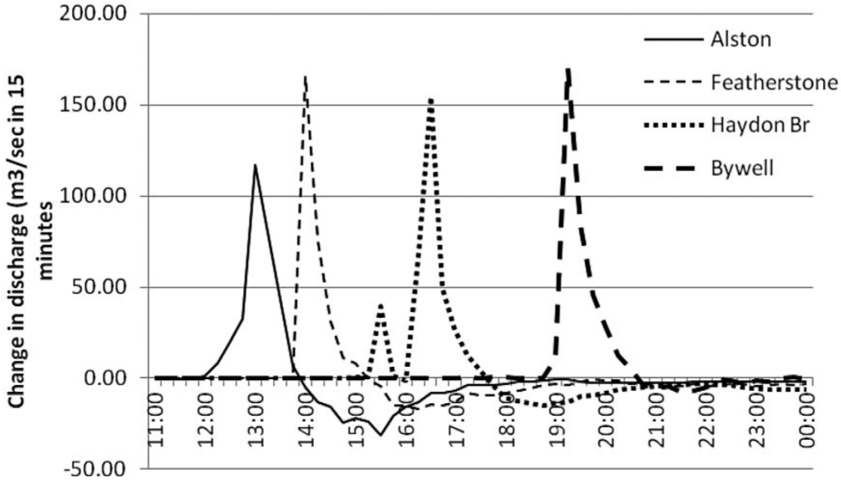

Figure 8 Change in discharge between successive 15-min observations (rate of rise) (m^3/s) for flood event on the South Tyne and Tyne on 30 July 2002.

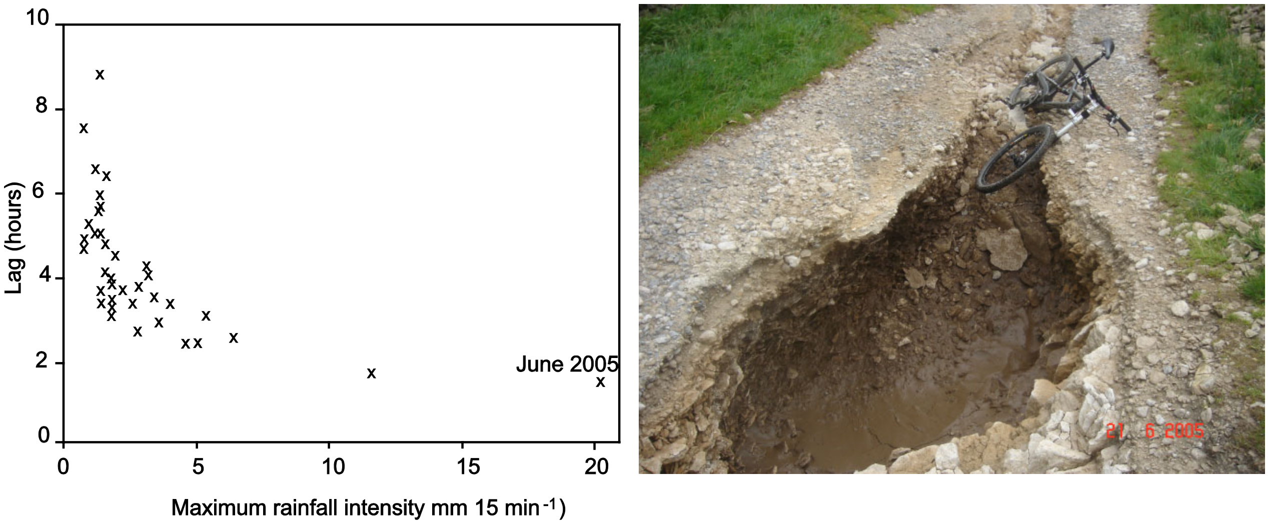

Figure 9 (a) Lag time plotted against maximum rainfall intensity for the River Rye at Broadway Foot (after Wass *et al*., 2008) and (b) gully created in the Rye catchment by the flash flood of June 2005.

from Kielder reservoir on the North Tyne (Johnson, 1988). The catchment characteristics and storm rainfall conditions which lead to flood wave steepening rather than attenuation need further investigation.

Speed of response

Response times of flash floods appear considerably reduced from 'normal' floods. Archer (1994) found very rapid response times for the Wansbeck flood (example 2). For the River Rye flood in 2005, the lag time was only one third of the 6 h averaged for other floods (Figure 9a; after Wass *et al*., 2008).

With respect to the 2004 Boscastle flood, HR Wallingford (2005) had to reduce the time to peak of the unit hydrograph by a half and even then underestimated the flow calculated from hydraulic considerations. While Kjeldsen *et al.* (2005) found no statistical evidence for a shortening of river response time with flow magnitude, Young and Beven (1994) and Ashfaq and Webster (2000) note the relationship specifically between rainfall intensity and response time. Wass *et al.* (2008) suggest a land phase mechanism for reduced response time where overland flow is concentrated into gullies, extending the channel network to make delivery to the river more efficient (Figure 9b). Analysis of travel time between gauging stations in examples 4 and 5 suggests that within channel wave, travel time is also reduced where such translatory waves occur. Wavefront velocities of 4.8 m/s were observed in the upper River Tyne and 3.4 m/s in the reach above the estuary in example 5.

Such changes in response time have serious practical consequences. The unit hydrograph-based rainfall–run-off method, updated as the Revitalised Flood Hydrograph Model (Kjeldsen *et al.*, 2005), is still used alongside the statistical method as a basis for flood risk estimation and design in Britain. The method uses a fixed time to peak of the unit hydrograph (or a reduction of one third for reservoir flood estimation). However, for intense rainfall events, use of the rainfall run-off method could seriously underestimate peak flows. The SINATRA project will develop new techniques which can reliably model and predict flash flood characteristics of very rapid rate of rise, steepening downstream wavefront and reduced lag times.

Catchment vulnerability

Steeply rising wavefronts seem to occur more commonly on steep upland catchments (examples 1, 2 and 5). However, such wavefronts can also occur on lowland catchments (e.g. example 4, River Wansbeck), implying that with rainfall of sufficient intensity, a flood wave with near vertical wavefront can be generated on virtually any catchment. This view is supported by observations of flash floods on chalk streams and dry valleys (Lud at Louth, May 1920: Clark and Arellano, 2004; Berkshire Downs[11] May 1993: Pike, 1994; Yorkshire Wolds[12]: Hood, 1892). The extraordinary flood of May 1920 on the Lud at Louth, which killed 23 people (in 20 min) and made 1000 homeless, was characterised by extremely rapid rise in level. In one small tributary, the water level was reported to have risen by 4.6 m in 15 min (Clark and Arellano, 2004).

While antecedent catchment wetness may contribute to flash flood vulnerability, the example of the Wansbeck where the flash flood was preceded by a very dry summer and the initial channel flow of 0.6 m^3/s was at only the 70% exceedance level shows that with sufficient rainfall intensity, overland flow occurs regardless of initial catchment wetness.

Flash flood impacts

Examples 2, 4 and 5, where peak flood level was not of extreme magnitude, did not result in any loss of life. However, a historical review of flooding in northeast England (Archer, 1992) notes a number of occasions when people were drowned by rapid rise of river level on the Tyne and Tees while crossing stepping stones or marooned on low islands.

A search through flood history reveals many occasions when rapid rise in level rather than the peak level or discharge was primarily responsible for flood deaths. Few *et al.* (2004) note that, 'The speed of onset of floodwaters is a key factor determining the number of immediate flood-related deaths; few deaths from drowning occur during slow rising floods'. Flash floods provide serious risks to people trapped in their homes and work places by rapid rise of water level caused by intense rainfall, sometimes remote from where the rainfall occurred.

Archer and Fowler (2014) reported on perhaps the most fatal of flash floods (excluding dam breaks) in the last 200 years in Britain. In July 1838, severe thunderstorms over Yorkshire and Lancashire caused multiple loss of life. The most tragic incident was at Barnsley[13] where 27 children drowned when flood water poured into a coal pit while three men drowned in another coal pit near Rochdale[14]; a boy was swept from a stable at Bradley[15] and another died at Bolton[16]. A similar incident in July 1846 at the East Wheal Rose Silver and Lead Mine[17], about eight miles north of Truro in south-west England caused 39 deaths when flood water from an intense, localised thunderstorm burst into the pit. The disabled or the elderly and very young are often the worst affected; e.g. in May 1807 water from Silkstone Beck[18] suddenly burst into a house where a woman and her four children were seated. The water rose so rapidly that it was with the greatest difficulty she saved herself and three of the children by rushing upstairs. The fourth, a 7-year old girl, ascended the 'sinkstone' but perished. In an adjoining house, a woman and her two grandchildren also drowned.

Defining flash floods

It is clear from the literature that there is no universal definition of a 'flash flood'. Definitions of flash floods may include those resulting from dam and levee failures, from release of water impounded by ice jams or glacial lake outbursts, or may be regional in nature. The definition provided here is restricted to flash floods caused by intense rainfall. Gaume *et al.* (2009) suggest that flash floods are generally associated with rainfall exceeding 100 mm in a few hours but the threshold for occurrence of flash flooding may differ regionally or occur from longer duration rainfalls with accumulations of several hundred millimetres, not uncommon in the Mediterranean region but extremely rare in Britain.

Definitions also refer to lag time, rapidity of onset, peak flow and volume, and impact in terms of risk to life and property. Rainfall forecast alarm thresholds for 1 h, 3 h and 6 h are used by the UK Flood Forecasting Centre to identify possible flash floods on rapid response catchments. These are predicated on whether a catchment is wet(dry) and are typically > 40 mm(80 mm) in 1 h, > 66 mm (106 mm) in 3 h or > 80 mm (120 mm) in 6h (Pollard, 2014). However, rainfall depths and durations required to cause flash flooding will vary with topography, channel characteristics and antecedent conditions (Hurford *et al.*, 2012)

Typically, a catchment response time of < 6 h is used to identify flash flooding (Georgakakos, 1986). However, it is important to distinguish between hydrological response time from rainfall to flood peak and 'threat response time' from initial perception of a flood to the occurrence of a level posing a threat to life and property. Examples 4 and 5 show that although lag time in fluvial floods can be 6 h or more, the 'threat response time' is at most a few minutes. The key characteristic of a flash flood, whether pluvial or fluvial, is the rate of rise in level and velocity. For river flows, such measures are readily obtained from gauged river levels as shown in Figures 5b and 8. Measurement is not practical for pluvial floods but hydraulic modeling with known rainfall intensities can provide insight on flood pathways, location of ponding, depths and velocities (e.g. Glenis *et al*., 2013). While potential impact in terms of risk to life is an important characteristic of flash floods, the examples illustrate that very high total rainfall or peak discharge are not necessary conditions for flash flooding. However, when associated with extreme rates of rise, they pose the most serious threat to life, as exemplified at Lynmouth.

The following definition of a flash flood relevant to Britain is proposed:

> A flood resulting from short duration intensity of rainfall typically > 40 mm in 1 h, usually convective, that exceeds drainage capacity in urban areas or infiltration capacity in rural areas and hence can flood land and property far from rivers. Threat response times from recognizing the flood potential to experiencing its threat to life and property are generally < 1 h but may be virtually instantaneous with near vertical wave fronts in river channels; river users and floodplain residents may be endangered by rapid rates of rise in river level which may be enhanced by failure of upstream structures or antecedent saturation of the catchment. Flash floods may cause serious erosion of hillsides and river channels and may carry heavy loads of floating debris and boulders which may be deposited in berms and terraces.'

Conclusions

From the above discussion the following conclusions are drawn:

1. Flash floods may be localised or widespread. They may arise from individual convective cells, or as mesoscale convective systems.
2. River flash floods are characterised by rapid rates of rise which may take the form of a visible 'wall of water'.
3. Such rapid rates of rise in water level do not require the failure of an upstream structure but may be generated by rainfall events of extreme short period intensity in the headwaters.
4. Steep wavefronts may be transmitted downstream for long distances and may become steeper in their descent.
5. Response times of floods (lag from rainfall to flood peak) arising from intense short duration rainfall appear considerably reduced from 'normal' floods.
6. Initiation of steeply rising wavefronts is more common on steep upland catchments. However, where short period rainfall intensity is sufficient, such wavefronts can also occur on lowland catchments.
7. Risk to life is greater in flash floods than 'normal' floods even if these have much higher peak magnitude. The speed of onset is key to risk to life.
8. Pluvial floods are generally caused by intense short-duration rainstorms which cause widespread and severe localised flooding. This flooding often follows reactivated ancient river channels in urban areas.
9. Historical information on flash floods, both pluvial (e.g. Newcastle 2012) and river floods (e.g. River Wansbeck 1994), can help to clarify the risk of occurrence of such rare events.

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