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The characteristics of 'abrupt wave front' floods on Pennine catchments, northern England, and their transmission downstream

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ABSTRACT

Visible flood waves, described as abrupt wave front events (AWF), have been identified on rivers in northern England rising in the Pennines, from both historical and recent gauged data. The focus of this paper is on the characteristics of two gauged AWF events on the Rivers Wear and Tees in 1983 and their comparison to 'normal' floods. The description and analysis is based on contemporaneous photographs and observations and on digital level and flow records. The rapid 15-min rise in these events is compared with the maximum rate of rise in annual maximum peak floods by comparing flood hydrographs. The propagation of the flood wave downstream is illustrated. The 15-min increase in discharge is compared in relation to the peak flow for AWF and normal floods at different gauged locations down the catchments showing striking differences. The character of the AWF response in the vertical or near-vertical wave front and rapid increase in both level and discharge points to the occurrence of kinematic shock waves.

Key words: abrupt wave front, flash flood, kinematic shock, walls of water

HIGHLIGHTS

- Visible wave fronts, described as abrupt wave front events (AWF), are described on the Rivers Wear and Tees in northern England.
- The sudden rise in level and discharge is a serious hazard, separate from peak flow.
- AWF events differ from normal flood events on the same catchment.
- AWF events remain a hazard for tens of kilometres downstream.
- AWF events are kinematic shock waves.

INTRODUCTION

Extremely rapid rates of rise in level and discharge in a subset of flash floods ('abrupt wave front floods' (AWF)) are separate hazards from peak level. Such flood events were investigated for Pennine catchments in northern England (Archer & Fowler 2021). Historical data for 122 events are extracted from a chronology of flash floods for Britain freely available on the JBA Trust website (https://www.jbatrust.org/how-we-help/publications-resources/rivers-and-coasts/uk-chronology-of-flash-floods-1/), and hereinafter referred to as 'The Chronology'. Until recently, such events have been attributed to ephemeral upstream landslides or bridge failure but are now shown to occur predominantly as the result of extreme rainfall on steep upland catchments without upstream blockage but can be transmitted downstream with a steepening front for tens of kilometres (Archer & Fowler 2021). Historically, observers have frequently described such events in Britain as 'walls of water' including the flood of 17 July 1983, reported below. Similarly, Viggiani (2020) lists 20 'instant floods' from various parts of the world which caused death by drowning. Collischonn & Kobiyama (2019) also note the relatively frequent occurrence of 'cabeça d'água' in southern Brazil as a type of flood in which it is possible to clearly observe the arrival of the flood wave as a visible discontinuity of flow and water level. The focus of this paper is on two such events on the Rivers Wear and Tees in 1983.

The hazard and frequency of events with very rapid rates of rise in level and discharge is not adequately recognised in Britain. AWF events are a threat to river users even when the peak flow is not severe or extreme. The principal objective of the

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paper is therefore to raise awareness and to encourage development of procedures with agencies responsible for monitoring, forecasting and warning to river users.

The geographical context

The River Tees rises on the highest point in the Pennines at Cross Fell 893 m OD while the highest point in the Wear catchment is at 747 m OD on Burnhope Seat (Figure 1). The greater part of both catchments lies between 400 and 600 m as a rolling plateau with predominantly peat moorland but with steeply sloping tributaries falling to the Wear and Tees. The main stem of the Tees between the source of the floods and the gauging station at Middleton is also very steep, falling 162 m in 23.5 km between the Langdon Beck gauging station and the Middleton gauging station (Figure 1) including the 21 m High Force waterfall and a series of low falls and rapids at Low Force. The Wear main channel is less steep with a fall of approximately 50 m in 10.8 km from the tributary sources of the flood to the Stanhope gauging station. It was on the headwaters of tributaries, straddling the interfluve that two remarkable storm and flash flood AWF events occurred on 7 June and 17 July 1983.

DATA

The description and analysis is based on contemporaneous observations of the effects of the floods and interviews of affected residents and on archived rainfall and level and flow records at 15-min intervals for the period 1982–2014 held at the Environment Agency.

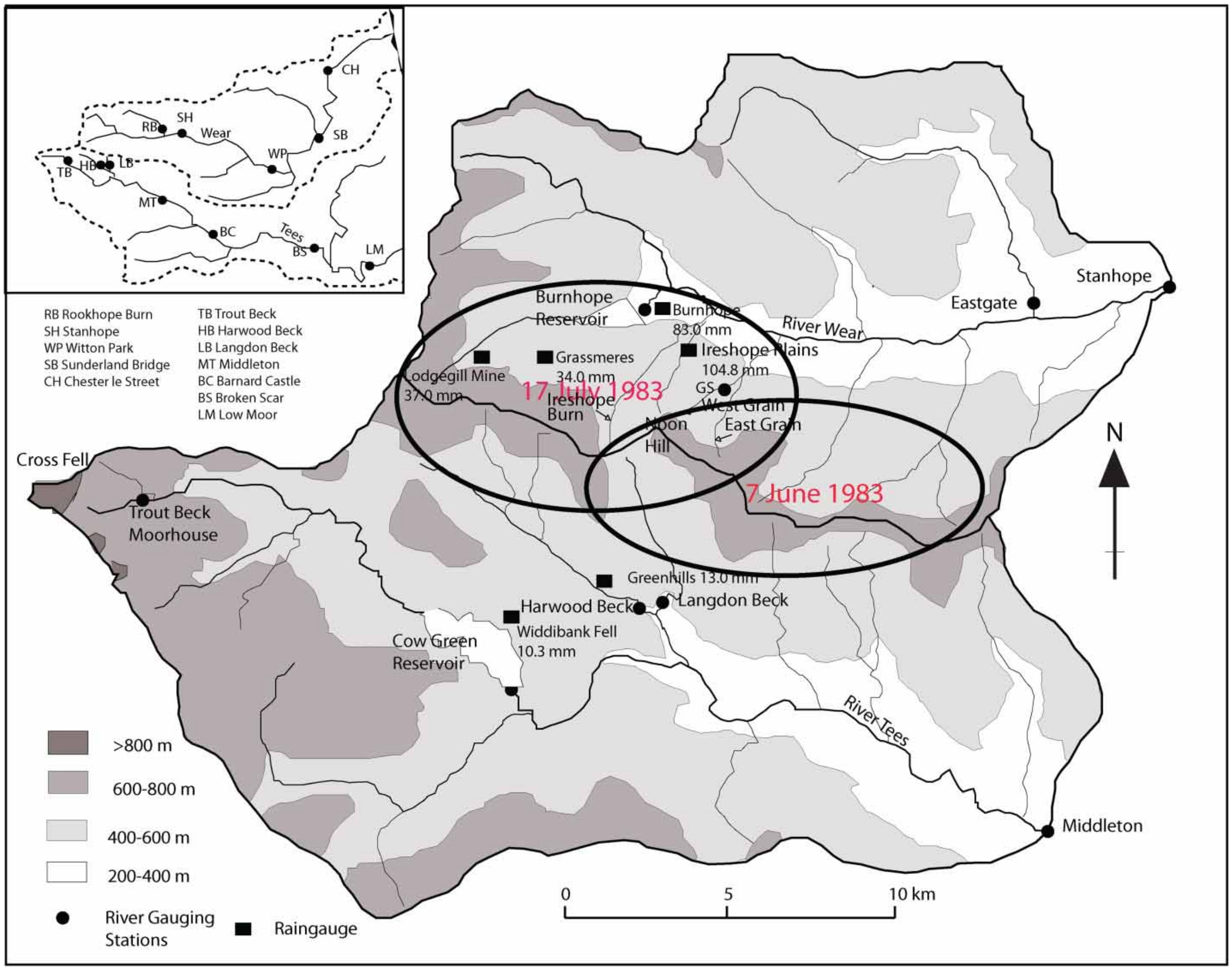

Figure 1 | The Upper Wear and Tees catchments showing the approximate location of the intense rainfall (and daily rainfall 17 July) which caused the abrupt wave front events. The inset shows gauging stations on the main stem of the Wear and Tees.

The storm events

17 July 1983 Wear catchment

The flood of 17 July is described by Carling (1986a) and Archer (1992) but is considered here in the context of the concept of AWF floods. July 1983 had at the time the highest recorded July temperature in central England and is now only exceeded by 2006 (Met Office Hadley Centre 2022). In the northeast temperatures reached 29° on 14th and 15th July. Monthly rainfall totals were less than 25% of the average for many stations in England but thunderstorms were widespread during the month including the storms of 17 July in the upper Wear and Tees. The single recording gauge in the storm area at Burnhope Reservoir registered the start of the storm at 15.24 but failed after a few minutes probably as the result of a lightning strike. The adjacent daily gauge registered a total of 87 mm. A rainfall of 104.8 mm was measured at Ireshope Plains between 15.30 and 18.00 but the observer noted that the most intense rainfall fell in 1.25 h between 15.45 and 17.00. The observer also noted that the storm was more intense over the moors to the south. The most intense rainfall seems to have occurred on Noon Hill on the margins of which five peat slides occurred, three towards the Ireshope Burn, and one each to the West Grain (Wear catchment) and the Langdon Beck (Tees catchment) (Carling 1986b; Archer 1992). It was from these three tributaries that the observed AWF on the main river gauging stations at Stanhope (Wear) and Middleton (Tees) originated.

The West Grain catchment rising on the northwest slope of Noon Hill leads to a steep channel towards a gauging structure (1.59 km^2) and recorder house which provided an early indication of the progress of the flood wave. The flood overtopped the roof of the gauging hut (Figure 2(a)) and removed the slate roof. A large boulder was projected through the broken wooden shutters and destroyed a level recorder (Figure 2(b)). The largest transported boulder can be seen in front of the gauging hut with a figure for scale. Behind the gauging hut can be seen a swash mark on the grass and the destroyed fencing. Downstream, a road culvert (catchment area 1.86 km^2) was surcharged; the water backed up and flowed over the road. At this point, Carling (1986a) estimated the peak discharge from culvert geometry as 22 m^3/s. An alternative assessment of a peak flow of 16 m^3/s was based on the size of boulders transported. The West Grain joins the East Grain and together the catchment area to the Wear confluence is 5.3 km^2. There is no available evidence of the augmentation of the flow downstream from the road culvert.

The Ireshope Burn rises on the north side of Noon Hill and the occurrence of three peat slides suggests the storm intensity was at least of the same order as on the West Grain. Information was gained from interviews with residents near the mouth of the stream which suggested a steep wave front which dislodged two riverside caravans and carried one (unoccupied) into the River Wear and another (occupied by a family) carried off but held against a wall until the wave subsided. The rapid rise in level precluded the possibility of escape. The catchment area of the Ireshope Burn to the Wear confluence is 7.9 km^2.

The raingauges on the Burnhope Burn indicate that significant flow could also have arisen on that catchment but the reservoir, drawn down to summer levels, captured most of that flow and there was no overflow.

At the Stanhope gauging station (catchment area 172 km^2), 10.5 km downstream from the East/West Grain confluence the discharge rose from 0.76 to 71 m^3/s between 16.15 and 16.30 with an equivalent rise in level of 1.53 m. The peak flow of

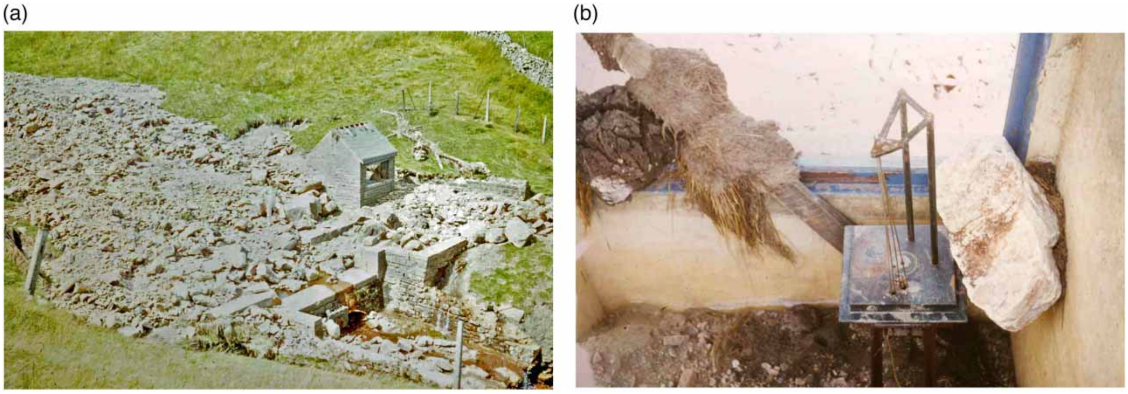

Figure 2 | (a) The gauging structure on the West Grain showing the boulder accumulation, the damaged gauging hut, the swash mark on the grass and the normal summer low flow. (b) The interior of the gauging hut from the destroyed roof with the level recorder pinned down by a boulder.

97.8 m^3/s was 1 h later at 17.15. A police observer along the river reported a 'wall of water' to the flood warning control room at Northumbrian Water.

The estimated flow from the 1.86 km^2 catchment of the West Grain of 16–22 m^3/s represents 17–23% of the peak flow at the Stanhope gauging station (172 km^2). With similar intensity of runoff, the peak flow at Stanhope of 94 m^3/s could have been created from an area of 8–11 km^2. Since the combined area of the Ireshope Burn and West/East Grain catchments is 13.2 km^2, this small contributing area seems credible. The total volume of storm flow at Stanhope was approximately 1,410,000 m^3. Assuming contributing areas of 8 or 13.2 km^2, the effective rainfall for the storm was 176 or 107 mm.

At Witton Park (catchment area 455 km^2), the next gauging station, a further 23.5 km downstream, the flood wave was attenuated and the peak discharge reduced to 77 m^3/s (Figure 3(a)). However, the rapid rate of rise persisted with a 15-min rise in level and discharge at 20.15 of 1.30 m and 51.1 m^3/s, the Rank 1 event in a 30-year period. The storm volume was only 3% different from Stanhope so it is concluded that there was no significant lateral storm inflow between the stations.

The next gauging station downstream at Sunderland Bridge (catchment area 658 km^2) was out of operation during the event, and at Chester le Street (catchment area 1,008 km^2), the rising limb was much less steep with the 15-min rise less than the median annual maximum.

17 July 1983 Tees catchment

Noon Hills was again the principal source of the Tees flood with the water discharging into the Langdon Beck (catchment area 13 km^2) and Harwood Beck (25.1 km^2). The records from the two gauging stations near their confluence do not permit an assessment of the maximum 15-min rate of rise and their timing owing to blockage of inlet pipes by peat sediment load generated on the headwaters. At the Langdon Beck, the peak level was surveyed from wrack marks at 1.66 m (35.0 m^3/s), the second highest peak level in the record from 1970 to 2020, rising from an initial level of 0.07 m (0.02 m^3/s). The observer and photographer of the Langdon Beck flood specifically referred to the occurrence of a wall of water (Carling 1986a). The turbulent flow and entrained peat is shown in Figure 4 just upstream from the confluence with the Harwood Beck. At the Harwood Beck, the peak level was 1.62 m (57.8 m^3/s), rising from an initial level of 0.11 m (0.06 m^3/s). The flood wave on the Langdon Beck preceded the wave on the Harwood Beck, presumably because of the longer travel distance from the storm rainfall to the outlet than on the Langdon Beck (Figure 1).

At the Middleton gauging station (catchment area 242.1 km^2), the flood wave arrived at 17.15 when the level rose from 5.2 to 60.0 m^3/s (from 0.53 to 1.45 m). However, the contributing waves seem not to have completely merged as the first peak was followed by a brief trough, then a rise to a second main peak of 85.7 m^3/s at 18.15. The combined peak flows from the Langdon Beck and the Harwood Beck are sufficient to account for the peak at Middleton without any further contribution.

A chart record from Barnard Castle gauging station (catchment area 509.2 km^2), 16.4 km downstream shows a sudden rise from 0.52 to 1.17 m (6.3–77.6 m^3/s) at 19.30. However, the high level was maintained for 2 h, indicating that the contributing waves have still not fully merged.

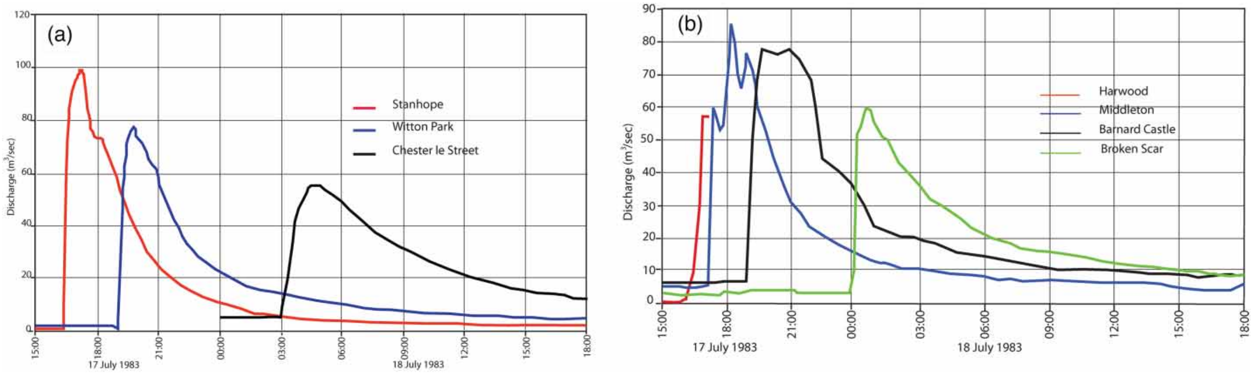

Figure 3 | Hydrographs for the flood event of 17 July 1983 for gauging stations on the River Wear (a) and on the River Tees (b). *Note:* Harwood stilling well blocked after the peak and Barnard Castle may also have been affected by blockage.

Figure 4 | The lower Langdon Beck just upstream from its confluence with the Harwood Beck on 17 July 1983.

At Broken Scar gauging station (catchment area 818.4 km^2), a further 28.4 km downstream, the hydrograph shows considerable attenuation with the initial increase in level from 0.52 m at 23.45 to 1.22 m at 00.30 on 18th (3.5–60.0 m^3/s). However, the maximum 15-min rise in discharge was 41.6 m^3/s, an increase which could still endanger river users.

7/8 June 1983

The June 7/8 1983 flood entirely escaped notice at the time both by the press and by Northumbrian Water, then responsible for flood risk management and warning. The measured rainfall for the event, although heavy, was insufficient to account for the extreme flow (Ireshopeburn – 30.7 mm; Burnhope – 27.5 mm and Greenhills – 33.1 mm). The most significant feature of the storm was the fact that it caused an AWF on the Wear and Tees at Stanhope and Middleton at exactly the same time of 01.45. This observation provides conclusive evidence that AWF floods are not necessarily caused by landslide blockage and subsequent release as this would require simultaneous blockages on both sides of the divide (Archer 2021). On both rivers, the recession was rapid and by the following morning, the level had fallen to a normal summer level. The AWF observed on the Langdon Beck indicates that intense storm rainfall occurred on its headwaters at Noon Hill, the same location of intense rainfall as in the 17 July flood. The June storm may therefore have influenced the peat and substrate making it more vulnerable to the peat slides which occurred in the July storm.

7/8 June 1983 Wear catchment

Figure 5(a) shows successive hydrographs of flow at stations down the River Wear. At Stanhope, there was a 15-min rise in discharge from 2.2 to 74.4 m^3/s and an immediate fall of 10.0 m^3/s in the following 15-min interval. Equivalent level changes

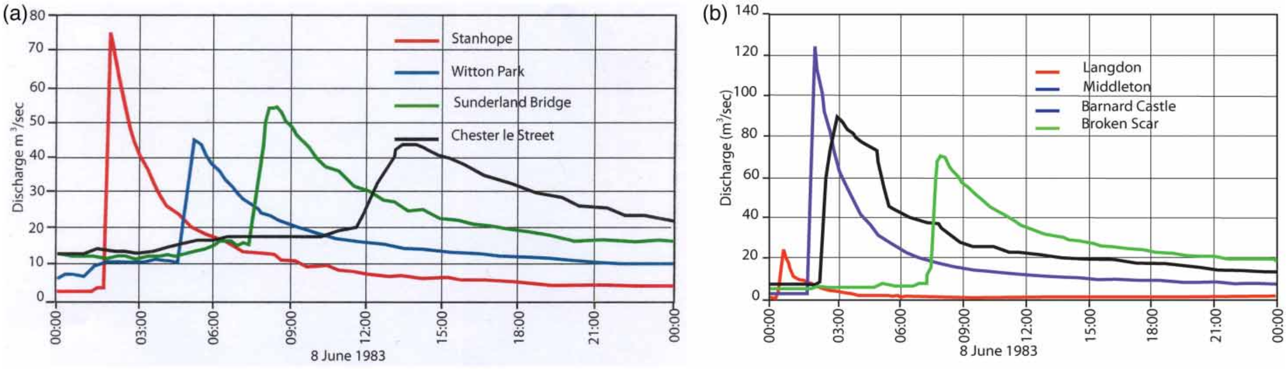

Figure 5 | 7/8 June 1983 hydrographs of abrupt wave front propagation (a) through the River Wear and (b) through the Tees catchment.

were from 0.28 to 1.71 m, a rise of 1.44 m. Owing to the sharpness of the peak, there was much more attenuation of the peak than on the 17 July storm with the peak at Witton Park reduced to 44.2 m^3/s at 05.15, a reduction of 41% from Stanhope. The maximum 15-min rise in level was 25.0 m^3/s (0.65 m). Downstream hydrographs were also affected by local tributary inflows with significant increases in initial flow before the most rapid rise. At Sunderland Bridge, the maximum 15-min rise reduced to 16.6 m^3/s (0.16 m).

7/8 June 1983 Tees catchment

The storm seems to have overlapped with the east side of the storm of 17 July causing an AWF on the Langdon Beck with an instantaneous rise in level from 0.12 to 1.38 m at 00.00 on 8 June. However, the Harwood Beck was unaffected. At the Middleton, the discharge rose from 3.1 to 123 m^3/s at 01.45 and fell in the next 15-min interval to 108 m^3/s. Although the Langdon Beck rise in level was rapid, the associated discharge was insufficient to account for the flow at Middleton, and further inflow from downstream tributaries is assumed. The Barnard Castle record appears to be influenced by partial blockage of the stilling well with the rise from 7.9 to 88.7 m^3/s spread over 45 min and the recession broken. The Tees was not much influenced by tributary inflows, but at Broken Scar, there was a gradual increase over a period of 6 h before a 1-h rise from 7.7 to 69 m^3/s with a maximum 15-min increase of 44.3 m^3/s. The equivalent rise in level was only 0.36 m given the insensitivity of the multiple-crested weir.

COMPARISON OF AWF AND NORMAL FLOOD HYDROGRAPHS

Hydrograph profiles

That AWF are categorically different from normal floods on the River Tees at Middleton is clearly illustrated in Figure 6, where the flood events are centred on the flood peak. The near instantaneous rise in level for AWF floods is compared with the gradual approach to the peak in both winter and summer annual maximum floods. All five summer AMAX floods are included in the comparison and the five winter events selected had the highest winter peaks in the record.

Although the focus here is on the floods of 1983, there were four other AWF events at Middleton in the record period from 1982 to 2014 during which the water level rose by more than 1 m in 15 min (Table 1). Three of these occurred at the same time as AWF events on the South Tyne with which the Tees shares headwater sources on the Cross Fell massif. On 20 July 2002, a recording raingauge at Alston on the South Tyne recorded 26.2 mm in the first 15 min of the storm. At Middleton on the Tees, the water rose 1.12 m (76.3 m^3/s) in 15 min, while on the Tyne, the AWF persisted to the lowest gauging station at Bywell with a catchment area of over 2,000 km^2 (Archer & Fowler 2018). Similarly, AWF events were experienced on the Tees and South Tyne on 9 August 2004 and 20 July 2007. On both occasions, thunderstorms were widespread and properties

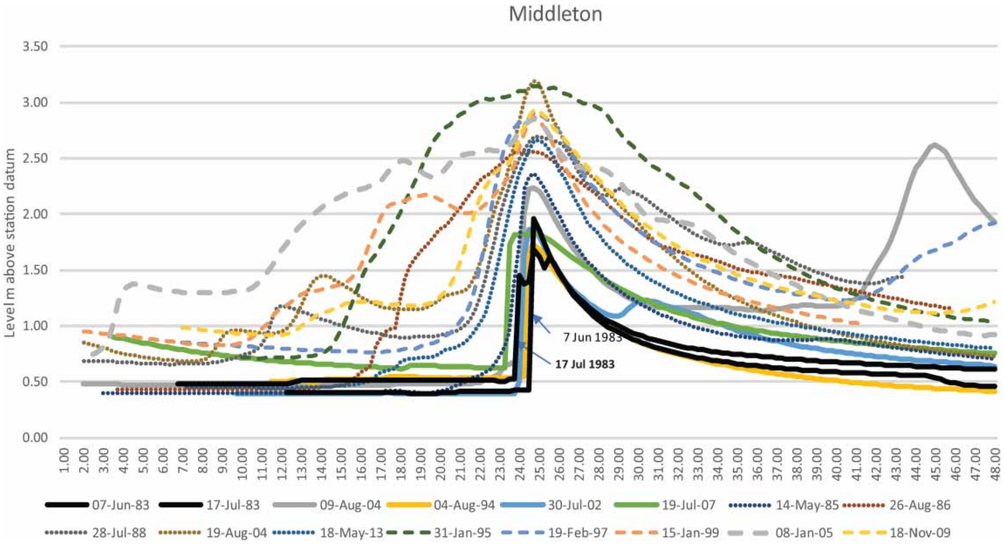

Figure 6 | Comparison of hydrographs between abrupt wave front events and 'normal' annual maximum peak flood events, centred on the flood peak. AWF are shown in bold, winter floods are dashed and summer floods are dotted.

were flooded from surface water following intense rainfall. In addition, on 20 July 2007, the overflow of tributaries caused flooding in Alston, Haltwhistle and Bardon Mill and overwhelmed and nearly drowned a fisherman standing on a flood bank at the river's edge on the lower South Tyne (Archer & Fowler 2022). Flash flood hydrographs for the South Tyne are shown in The Chronology (Northeast region). On 4 August 1994, storms were more dispersed but a remarkable AWF also occurred on the lowland River Wansbeck (Archer 1994; Archer *et al.* 2016).

Table 1 shows the contrast in 15-min rise in level and discharge between AWF and normal summer and winter annual maximum floods. While the median rise in AWF floods was 1.12 m (81.4 m^3/s), for summer AMAX floods, it was 0.22 m (30 m^3/s) and for winter AMAX floods, it was 0.16 m (33.0 m^3/s). In each case, normal flood rises from heavy persistent rainfall were preceded and followed by similar but smaller 15-min rises.

Annual maximum flood peaks were, with one exception, greater than the peaks of the AWF floods, indicating the greater risk to property from such normal floods. However, the concentration on flood peaks as the only measure of severity misses the quite separate risk posed by the rate of change.

Comparison of 15-min rise in discharge and peak discharge with normal floods

These AWF flood peaks occurred within an hour of the most rapid rate of rise and in the case of 7 June 1983 recession followed immediately. The recessions were uninterrupted and the level fell within 24 h to a very low level, near the initial flow before the rise. The 15-min increase in discharge was a much higher proportion of the peak flow in these AWF events than in 'normal' floods as seen in Figure 7.

Such unusual catchment response has been quantified by a metric of hydrograph skewness as the volume before peak (VBP) of the hydrograph (Collischonn *et al.* 2017). The VBP is calculated as the proportion of total hydrograph volume that occurs before the occurrence of the peak. The VBP ranges from 0 to 1, with a low value when the hydrograph is positively skewed and a high value when the hydrograph is negatively skewed. An alternative simpler measure was used to demonstrate the contrast in hydrograph skewness between AWF and normal floods on the same catchments. The maximum 15-min rise in discharge (m^3/s) is compared as a percentage of peak discharge (m^3/s).

Table 1 | Maximum 15-min rise in level and discharge for events on the Tees at Middleton

Date	Maximum 15-min rise in level (m)	Maximum 15-min rise in flow (m^3/s)
Abrupt wave front events		
17 Jun 1983	1.53	119.9
17 Jul 1983	0.92	54.8
9 Aug 2004	1.23	118.0
4 Aug 1994	1.14	79.4
30 Jul 2002	1.12	74.3
19 Jul 2007	1.11	83.3
Summer AMAX		
14 May 1985	0.55	84.8
26 Aug 1986	0.25	17.1
28 Jul 1988	0.21	29.4
19 Aug 2004	0.22	60.0
18 May 2013	0.20	30.0
Winter AMAX		
31 Jan 1995	0.12	24.0
17 Feb 1997	0.24	40.0
15 Feb 1999	0.16	37.0
8 Jan 2005	0.19	21.0
18 Nov 2009	0.16	33.0

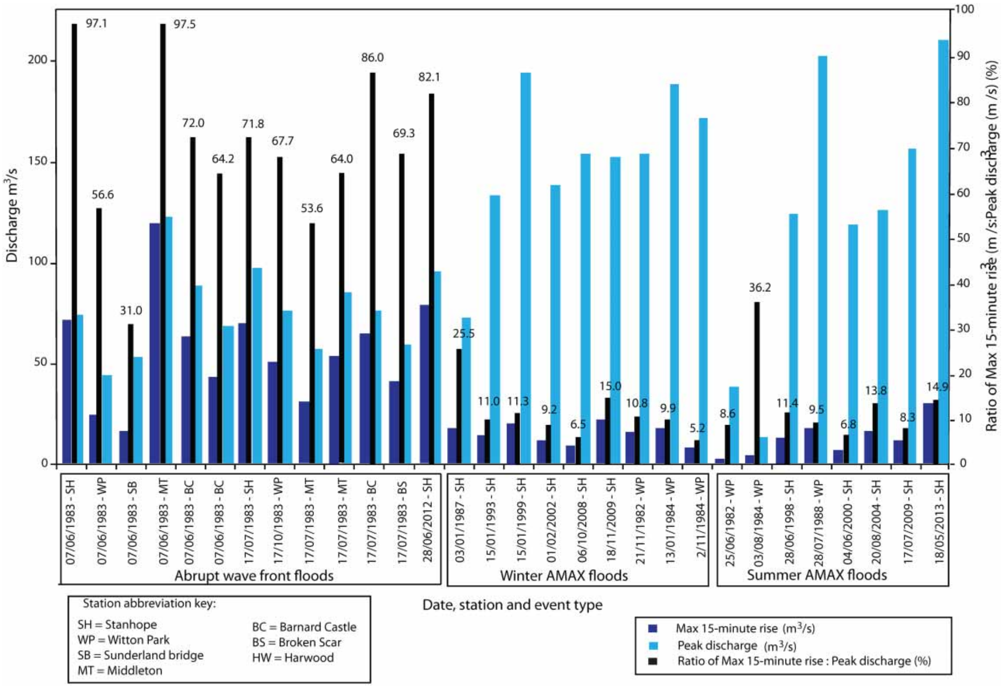

Figure 7 | Maximum 15-min rise (m^3/s) compared with peak discharge (m^3/s) (%) for AWF versus annual maximum (AMAX) winter and summer events.

There is a clear difference between these ratios for AWF events versus normal floods at the same gauging stations. AWF events have an average proportion of 72.4%, with a maximum and minimum of 97.5 and 31%, respectively, while normal annual maximum events have an average of 12.6%, with a maximum of 36.2% and a minimum of 5.2%.

DISCUSSION

Although not all rapid rise events on the basis of level records with a minimum 15-min time step can be conclusively defined as a 'wall' or a wave front increasing within a few seconds, observers' descriptions of the event of July 1983 and numerous historical events (Archer & Fowler 2021) provide strong collaborative evidence. The flow records are not in contrast with the occurrence of such phenomena. Even at a 15-min time step, AWF events are clearly different in character from normal flood events on the same catchment (Figures 6 and 7).

The Wear and Tees are not 'rapid response catchments' (Francis 2010) but these rare events are 'rapid response events'. But what are the causes of the difference between normal floods and AWF floods on the same catchment? The character of the AWF response in the vertical or near-vertical wave front and rapid increase in both level and discharge points to the occurrence of a kinematic shock wave (Archer 2022).

Lighthill & Whitham (1955) recognised the intrinsic non-linear property of kinematic flood waves and the associated shock potential, creating a visible discontinuity in the water level and discharge. However, until recently, the real-world occurrence of such AWF or shock waves has been doubted in spite of the theoretical basis for their existence. Such scepticism has been abetted until recently by the very rare observation of such events and it has been concluded by distinguished hydraulic engineers that shocks are simply a result of the approximations made in the development of the theory (Henderson 1966). However, nearly 300 historic and recent events have been described in the chronology of flash floods (Archer & Fowler 2021) and their occurrence can hardly be described as very rare. In this paper, we have given a detailed account of two events from which to account for the difference from normal floods.

Ponce (1991) notes that the shock is a direct consequence of the non-linear steepening tendency of the wave front, which is abetted when the following conditions occur:

First, the wave is kinematic as opposed to diffusive (or dynamic). Diffusion is a mechanism acting to oppose the non-linear steepening tendency. The more diffusive a wave is, the less kinematic, and therefore, the less the steepening tendency. The wave form at Stanhope (Wear) and Middleton (Tees) with the near-instant rise in level provides evidence that the wave is kinematic. Further downstream diffusion sets in and the wave front becomes less steep but diffusive effects seem to be greater on the river Wear than on the River Tees.

A second suggested requirement is that there is a low base-to-peak flow ratio. The steepening tendency is promoted when the flow is subject to large relative changes, with base flow being only a small fraction of peak flow. This is certainly the case both for the small West Grain catchment and for the larger upper Wear and Tees catchments. For the West Grain, Figure 2(a) shows the contrast between the normal very small summer flow observed a week after the event and the effects of the flood wave. At Stanhope, the flow increased in the 15-min interval from 2.19 to 74.4 m^3/s on 7 June and from 0.76 to 71 m^3/s on 17 July. At Middleton, the 15-min increase in flow was from 3.06 to 123 m^3/s on 7 June and from 5.19 to 85.7 m^3/s on 17 July. Figure 6 also shows the very low initial flow for the AWF events compared with normal winter and summer flood events.

Ponce (1991) also suggests that since wave steepening is gradual a sufficiently long channel is necessary to give the shock a chance to develop. Distance from the West Grain confluence to the Stanhope gauging station on the Wear is 10.8 km with a fall of 48 m and on the Tees from the Langdon Beck confluence to the Middleton gauging station is 23.5 km with a fall in level of 162 m. However, Ponce suggests strong steepening tendencies may require a shorter reach, and in the case of the steep West Grain, there is strong observational evidence that an AWF was already in existence within 3 km of the source of the storm – notably the swash mark of a wave on the grass (Figure 2(a)). Several other Pennine catchments where AWF events were observed on areas less than 5 km^2 are included in the Chronology. It is postulated that the larger discharge from the Ireshope Burn steepened and merged with the wave from the West Grain in the main Wear channel.

A further condition for shock development is that the channel is hydraulically wide, that is, one in which the wetted perimeter is nearly constant where the wetted perimeter increases very little in comparison with the increase in flow depth and area. This condition may be satisfied for in-bank flows as was the case for the Wear and Tees for these two events. The steepening tendency is counteracted and shock development is arrested in shallow-overbank flow situations but may still occur in extreme events such as the River Rye at Helmsley (Wass *et al.* 2008) or the Boscastle flood (Fenn *et al.* 2005).

Ponce also notes that the steepening tendency is promoted at high Froude numbers, at or above critical, to the point where the shock may develop. In hydraulically wide channels, high-Froude-number flows lack sufficient diffusion to effectively counteract the steepening tendency (Ponce & Simons 1977). Such high-Froude-number flows are rare in natural streams and rivers and are unlikely to occur on the main Wear or on the Tees with the exception of the steep rapid and fall section at High and Low Force. However, the steep tributaries on either side of the divide, where the AWF are generated, are likely to experience such high Froude numbers.

It is concluded that the events on the Wear and Tees in 1983 meet most of the conditions for kinematic shock specified by Ponce (1991). However, the most important feature of these events was the intense localised rainfall that generated rapid rates of rise on small upland tributaries, which were then transmitted downstream on the main rivers with a steepening front for more than 10 km. The account given here is descriptive and based on general observations but hydrological and hydraulic analysis with modelling capable of ‘shock capturing’ is required to provide a basis for forecasting and warning of the occurrence of such events including their generation and downstream transformation.

CONCLUSION

1. Five AWF events with 15-min rise in level greater than 1 m occurred on the Tees at Middleton and three on the Wear at Stanhope in a 30-year period. The hazard and the risk to life need to be taken more seriously for flood forecasting and warning procedures.
2. AWF events floods are categorically different from normal floods on the same catchment. The Rivers Wear and Tees are not normally ‘rapid response catchments’ but they experience rapid response events on rare occasions.
3. AWF floods are generated from intense rainfall on upland tributaries and very rapid rise in level already occurring on the West Grain catchment of 1.5 km^2.
4. Tributary flood waves merge in the main channel with the wave front steepening and persisting downstream for more than 10 km on the Wear and more than 20 km on the Tees.
5. Diffusion and attenuation occur further downstream but rates of rise 45 km downstream on the River Tees at Broken Scar are still sufficient to be a serious hazard to river users.

6. AWF floods differ from normal floods on the same catchment in their much more rapid short-period rate of rise and in terms of the comparative maximum 15-min rise in discharge as a percentage of peak discharge.
7. AWF floods satisfy conditions for characterising kinematic shock waves and in spite of previous reservations they should be recognised as such.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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