Received: 11 April 2023 | Revised: 18 March 2024 | Accepted: 25 March 2024

DOI: 10.1111/jfr3.12989

ORIGINAL ARTICLE

CIWEM Chartered Institution of Water and Environmental Management | Journal of Flood Risk Management | WILEY

Gauged and historical abrupt wave front floods ('walls of water') in Pennine rivers, northern England

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Funding information

JBA Trust, Grant/Award Number: project W20-3873; Kingdom NERC Flooding from Intense Rainfall programme, Grant/Award Number: NE/K00896X/1

Abstract

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 are investigated for Pennine catchments in northern England using both gauged and historical information. Gauged level and flow digital records at 15-min intervals provide recent data. Historical information for 122 AWF events is extracted from a chronology of flash floods for Britain. Historical AWF events are mapped and found to occur on every major Pennine catchment; catchment descriptors are derived as a basis for assessing catchment vulnerability. We discuss the disputed origin of AWF. Using gauged data, we contrast the rising limb of AWF and 'normal' floods. We investigate time series of historical AWF, noting a puzzling peak in the late 19th century. Current rainfall and river monitoring does not provide a reliable basis for understanding AWF processes or for operational response and we suggest improvements. Similarly, current models for design flood estimation and forecasting do not generate the observed rapid increase in level in AWF floods.

KEYWORDS

abrupt wave front, flash flood, hydrograph, Pennines, wall of water

1 | INTRODUCTION

Rapid rates of rise in river level and discharge in flash floods are separate hazards from peak flood level. We use both recent digital records and historical information to examine the location and characteristics of very rapid rates of rise in the Pennines of northern England. Here, we describe such events as abrupt wave front floods (AWFs) but often in historical accounts they have been described as 'walls of water'. We show how such AWF events differ in speed of response from typical catchment behaviour. We investigate time series of historical AWFs and attempt to explain their apparently anomalous variability, and address the practical issues of the provision of appropriate means of monitoring and modelling as a basis for forecasting and warning to respond to the hazard of AWFs.

Cornish (1907) provides an early description of such flood events on the Rivers Tyne, Tees, Swale and Ure:

> *'In certain rivers, of small depth and subject to sudden accessions from swollen tributaries, the " first rise " of water in the lower reaches frequently takes the form of a steep-fronted*

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https://doi.org/10.1111/jfr3.12989

> *wave, or bore, travelling downstream. On the Tees the phenomenon is called a roll-wave. It is described as 2 or 3 feet high, reaching from bank to bank. It was observed on no less than six occasions during the course of one summer and autumn. It is a source of considerable danger to anglers, coming as it does wholly without warning and travelling at a considerable speed'*.

There are further descriptive accounts of individual AWFs usually in desert environments (e.g., Hassan, 1990; Hjalmarson, 1984; Reid et al., 1994), but most descriptions of flash floods do not distinguish the separate hazard of rapid rise in level. However, Collischonn and Kobiyama (2019a) note that in Brazil AWF (cabeça d'água) where the water rises in a matter of seconds are relatively common and can occur on steep headwater streams in both arid and humid conditions, describing six occurrences between 2008 and 2019 causing 16 fatalities. Collischonn and Kobiyama (2019b) then describe the physical processes involved in the transformation of an ordinary flood wave into an abrupt wave front.

Based on previous analysis mainly on Pennine catchments, three features of AWF are elaborated (Archer et al., 2019; Archer & Fowler, 2018, 2021; Watkiss & Archer, 2023):

1. AWFs are generated by intense rainfall on headwater catchments; we have found little evidence for the occurrence of ephemeral upstream blockage and release.
2. Rapid rates of rise are a separate hazard from peak flow and may be a threat to life in floods of modest peak magnitude.
3. Rates of rise in an AWF are categorically different from 'normal' floods on the same catchment.

1.1 | The generation of an AWF

It has been frequently asserted by hydraulic engineers and by casual observers that rapid changes in water level are due to upstream blockages by landslides, trash dams or failed bridges and their subsequent release. For example, the severe flood at Carrbridge in Scotland in July 1923 wrecked four substantially built bridges and 600 yards of major roadway on high embankments; the Divisional Engineer of the Midland and Scottish Railway Company (British Rainfall, 1860–1991) reported:

> '*The oncoming avalanche of water indicates 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*'.

However, he adds the following reservation in reference to a similar flood in 1914, when a rail bridge was washed away causing loss of life:

> *'In 1914 on the other hand, 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'*.

Similarly, with respect to the severe Boscastle flood of 2004, when houses were severely damaged and 100 cars washed into the sea, Fenn et al. (2005) conclude:

> *'A number of eyewitnesses describe very rapid increases in water level over periods measured in minutes or seconds. These are reported both at Boscastle and Crackington Haven. A number of explanations have been offered for these rapid changes in water level… Though it is possible that the water levels were affected by trash dams upstream, it seems more likely that the observed changes in water level arose from changes in flow paths caused by events such as bridge blocking or a wall falling down in Boscastle'*

It is difficult to disprove the existence of ephemeral blockages. However, in the flash flood chronology of Britain (Archer & Fowler, 2021), where 289 flash flood events are identified as AWFs, there is scant evidence of upstream blockages. There is now sufficient evidence that AWFs can be generated solely by extreme short duration rainfall in upland catchments and can be transmitted downstream for more than 50 km, as on the Tyne in July 2002 (Archer & Fowler, 2018). Bridges may be demolished, not by the rapid build-up of a static head but by the combined impulse of a pre-existing wave front and scour around piers and abutments in the associated high velocities (Lamb et al., 2019; Van Leeuwen & Lamb, 2014). In June 1983, intense rainfall on the uninhabited and ungauged catchment boundary between the Wear and the Tees caused simultaneous AWFs of more than 1 m at downstream gauging stations on both rivers (Figure 1); this is highly unlikely to have been caused by

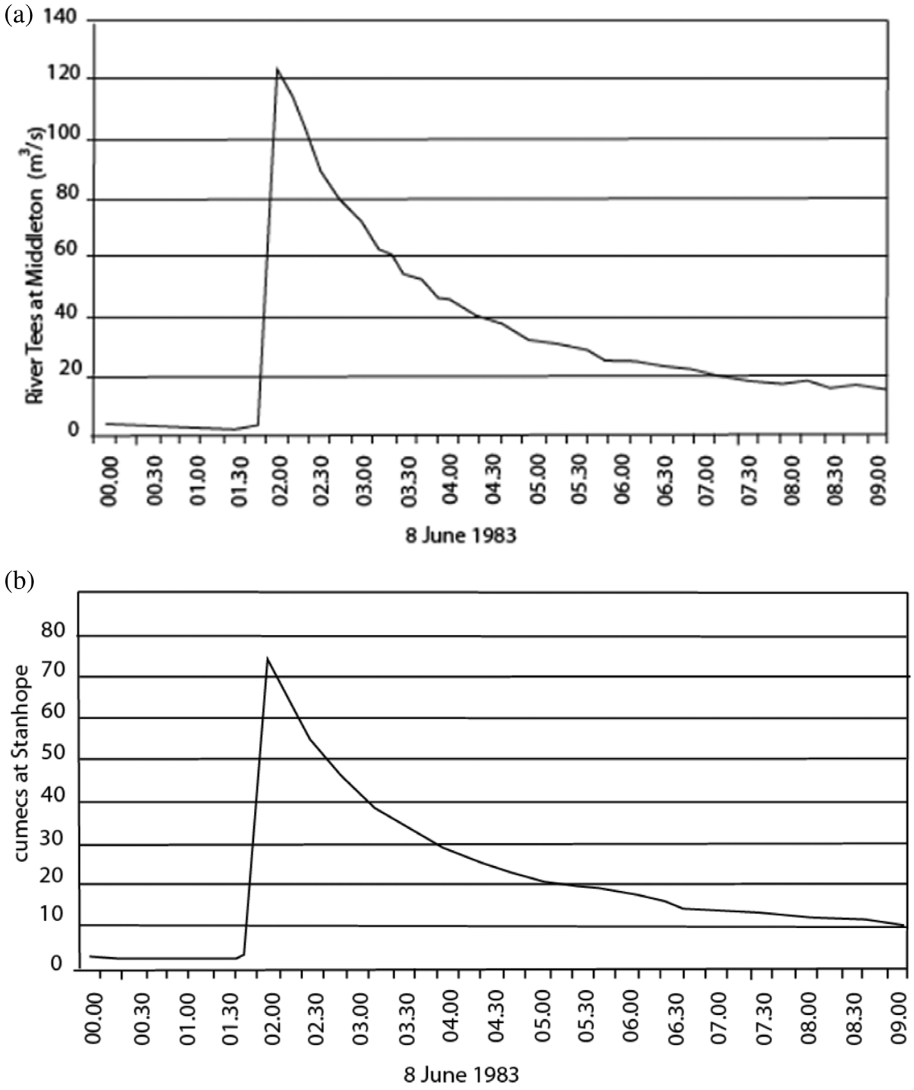

FIGURE 1 (a) Flow hydrograph for 8 June 1983 on the Tees at Middleton in Teesdale (catchment area of 242 km^2), 15-min rise in level and flow of 1.53 m and 120 m^3 s^{-1} respectively, and (b) Flow hydrograph for the Wear at Stanhope (catchment area 172 km^2), 15-min rise in level and flow of 1.44 m and 69 m^3 s^{-1}, respectively.

simultaneous blockages by debris flows in tributaries on both sides of the divide (Watkiss & Archer, 2023). We suggest that this event provides conclusive evidence that AWFs do not require an upstream blockage.

1.2 | The hazard of AWF

The hazard from AWFs depends not only on the rising level but also on the rapid increase in velocity and the impulse of the wave front; the combined increase in level and velocity generates large quantities of floating debris and entrained bedload. In a reported event on the River Tyne at Bywell, northern England, a current meter gauging from the cableway recorded point measurements >5 m s^{-1} before the suspension cable snapped and the current meter was lost (Hydrometric Technician, Graham, *pers. Comm.*). Even in the absence of floating debris, water flowing at this speed would pose a physical danger in depths as little as 0.25 m (Defra & Environment Agency, 2006). The above event was unfortunately not archived as the gauging was incomplete. However, based on the arrival time of the wave front between successive gauging stations at Haydon Bridge and Bywell on the River Tyne for the event of 30 July 2002 (described in Archer & Fowler, 2018), the celerity was 3.15 m s^{-1} over 34 km.

Rapidly rising river levels and high velocities are hazardous, but how rapid must 15-min rates of rise be, to be taken seriously as a hazard, which requires special forecasting and warning procedures? A rise of 1 m in 15-min is clearly a hazard for river users but much more serious if it occurs as a visible wall of water. Although a near-instantaneous rise of <0.6 m, with accompanying rapid increase in velocity, could still be considered a hazard, we have restricted our analysis of recent digital data to events with a 15-min increase in level of at least 0.6 m to allow for visual inspection of a manageable number of 15-min records.

The severity of the hazard also depends on the initial flow: whether the rise occurred abruptly from a low summer flow or as a component of rise in a severe winter storm. Winter events with high 15-min rates of rise are more likely to be preceded by an already rising hydrograph, with river users such as swimmers and anglers less likely to be in positions of risk. The following analysis therefore concentrates on summer events only, although rapid rates of rise in the middle of the rising limb resulting from severe persistent rainfall in summer are also discounted.

1.3 | Rates of rise in 'normal' and AWF floods

The rate of rise in AWF floods appears to be categorically different from normal floods on the same catchment. An example was observed on the River Wansbeck, where the Mitford gauging station (catchment area of 287.3 km^2) recorded a 15-min rise of 1.26 m on 3 August 1994, with an equivalent increase in discharge from 0.6 to 44.5 $\text{m}^3\,\text{s}^{-1}$ (Archer et al., 2017). The median annual maximum (AM) 15-min rate of rise in level is 0.30 m. This 1994 event is an outlier in the AM 15-min rate of rise series, and more than double the previously experienced AM in a 34-year period. The peak discharge was far short of the maximum recorded peak flow of 334.6 $\text{m}^3\,\text{s}^{-1}$ but still posed a serious hazard for river users at the town of Morpeth, a short distance downstream.

Occasionally, hazards of rapid rate of rise and peak flood combine to create more serious risk to river users, with examples from the extreme floods on the River Rye in North Yorkshire (Wass et al., 2008) and at Boscastle in southwest England (Fenn et al., 2005). The catastrophic flood on the River Rye at Broadway Foot (catchment area of 132 km^2) in June 2005 was extreme both in its peak discharge (400 $\text{m}^3\,\text{s}^{-1}$), which was 11 times the median AM flow (QMED) and in its rate of rise in level (an increase in water level of 1.43 m over 15-min, compared with a median AM rate of rise of 0.15 m).

Whilst AWFs do not necessarily occur in floods of exceptional peak magnitude, they do depend on the occurrence of very intense short duration rainfall; in the case of the Wansbeck a 15-min rainfall total of 30 mm was recorded in mid-catchment and daily rainfall of >70 mm at nine stations (Archer, 1994). In many cases, remote storms causing AWFs have no ground-based rainfall measurement. Further comparison of AWF and 'normal' flood hydrographs is made below based on a full record of 15-min gauged flows from Pennine catchments.

2 | DATA

2.1 | Gauged AWF data

With respect to gauged data, quantitative rates of rise were assessed as part of a UK Natural Environment Research Council research project, SINATRA (susceptibility of catchments to intense rainfall and flooding, UKRI, 2019). This project created a new database of rapid rises in river level and flow for England, Wales and Scotland using national 15-min level and flow data provided by the Environment Agency, Natural Resources Wales and the Scottish Environment Protection Agency. Peaks-over-a-threshold extremes of 0.25, 0.5, 1 and 2 h rates of rise in level and discharge were extracted from the entire national database of 15-min records. The 2578 station records were of variable length, but typically ranged from 1980 to 2014. This provided the opportunity to investigate the variability of rates of rise both within individual catchments and between catchments. However, full checking of these records (>1 million values for each station) was not possible within the scope of the SINATRA project. In this study, we have re-examined the hydrographs of the highest five ranked rates of rise for each station for Pennine catchments listed in Table 1 to validate or eliminate doubtful values and to identify sufficiently extreme values that might be considered AWFs.

We focus on 15-min rate of rise in water level as it is the immediate rise in level which is critical for the river user and this can be used to compare events. We note that it is not a perfect measure, as the rise in level for a given observed discharge depends on the configuration of the gauging weir or natural control. Rates of change in discharge obviously differ between catchments of different size, making comparisons between flood event severity problematic. A compound measure of change standardised by mean flow or QMED has been investigated but analysis is incomplete.

Figure 2 shows the location and magnitude of gauged AWFs in the Pennines over the period of digital record.

2.2 | Historical AWF data

Identification of historical AWFs is based on a flash flood chronology for Britain covering events from 1700 to 2020 (Archer et al., 2019; Archer & Fowler, 2021). The main source of information for the chronology was the British Newspaper Archive, an online source which can be searched by date, location, and newspaper (https://www.britishnewspaperarchive.co.uk/). At the beginning of the search in 2012 the archive contained 12 million pages but by 2020 when the search was completed the total number

TABLE 1 Number of observed abrupt wave front floods events in Pennine catchments from 1700 to 2020.

East of Pennines		West of Pennines	
Catchment	**Number of events**	**Catchment**	**Number of events**
Till	3	Eden	13
Coquet	2	Lune	7
Wansbeck	4	Wyre	4
Tyne	16	Ribble	4
Wear	5	Mersey	18
Tees	11		
Swale	7		
Ure	2		
Nidd	2		
Wharfe	5		
Aire	3		
Calder	13		
Don	3		
Total East	76	Total West	46

of pages had increased to 35 million (Archer & Fowler, 2021). The search was limited to April to October, a limitation justified by reference to the British Rainfall record of 'intense rainfall in short periods' where <2% of such reported occurrences are outside this summer period.

The chronology (JBA Trust, 2020) is available to download and is hosted on https://www.jbatrust.org/how-we-help/publications-resources/rivers-and-coasts/uk-chronology-of-flash-floods-1/. From a total of nearly 8000 flash floods for the whole of Britain, 289 were identified as AWFs, of which 47% occurred on catchments originating in the Pennine range. Incidents were identified as AWFs by descriptions of a visible wave as 'a wall of water', 'a breast of water', a wave resembling a bore, or as water rising at a rate of x feet in y minutes and substantiated by the associated impacts on river users (including deaths) and property. It was usually possible from the description to identify the point of observation of the AWF. A total of 122 Pennine events were identified and these are mapped in Figure 3. The dates and locations of AWF events by catchment are provided in the Data S1. Historical AWF events of sufficient severity to cause loss of life or the threat of drowning have occurred on every major catchment in the Pennines and Cheviot Hills, with the highest concentrations observed in the northern Pennines on the Tyne, Wear, Tees and Eden and the southern Pennines on the Calder and Mersey (Table 1).

We provide two example AWF descriptions from the chronology below.

The 9 July 1792 Diary of DC of Greenbank in Wyresdale, reported in Preston Chronicle 1 Apr 1865:

> *The River [Wyre] at Dolphinholme Factory came down in a breast 4 feet deep like as if a dam had been let off and nearly caught some women and children who were on the Warth; they were knee deep before they got out. It was said to have been caused by a cloud bursting in three places. At Dolphinholme in the street it was at a similar depth as at the factory.'* The catchment area to Dolphinholme is 74.9 km^2.

Westmorland Gazette 20 September 1968 reports:

> *'A man was rescued from the Hardraw Road. He was driving towards Sedbergh when he was suddenly met by a large wall of water from the nearby River Yore (sic Ure) opposite Pry House Farm. He was carried half a mile back on the Hardraw Road where the car became jammed against a wall. He scrambled out of the car which was quickly almost out of sight'*. The catchment area of the Ure to Pry House Farm is 48.7 km^2.

Archer and Fowler (2018) noted that flash floods originating in upland tributaries may be transmitted

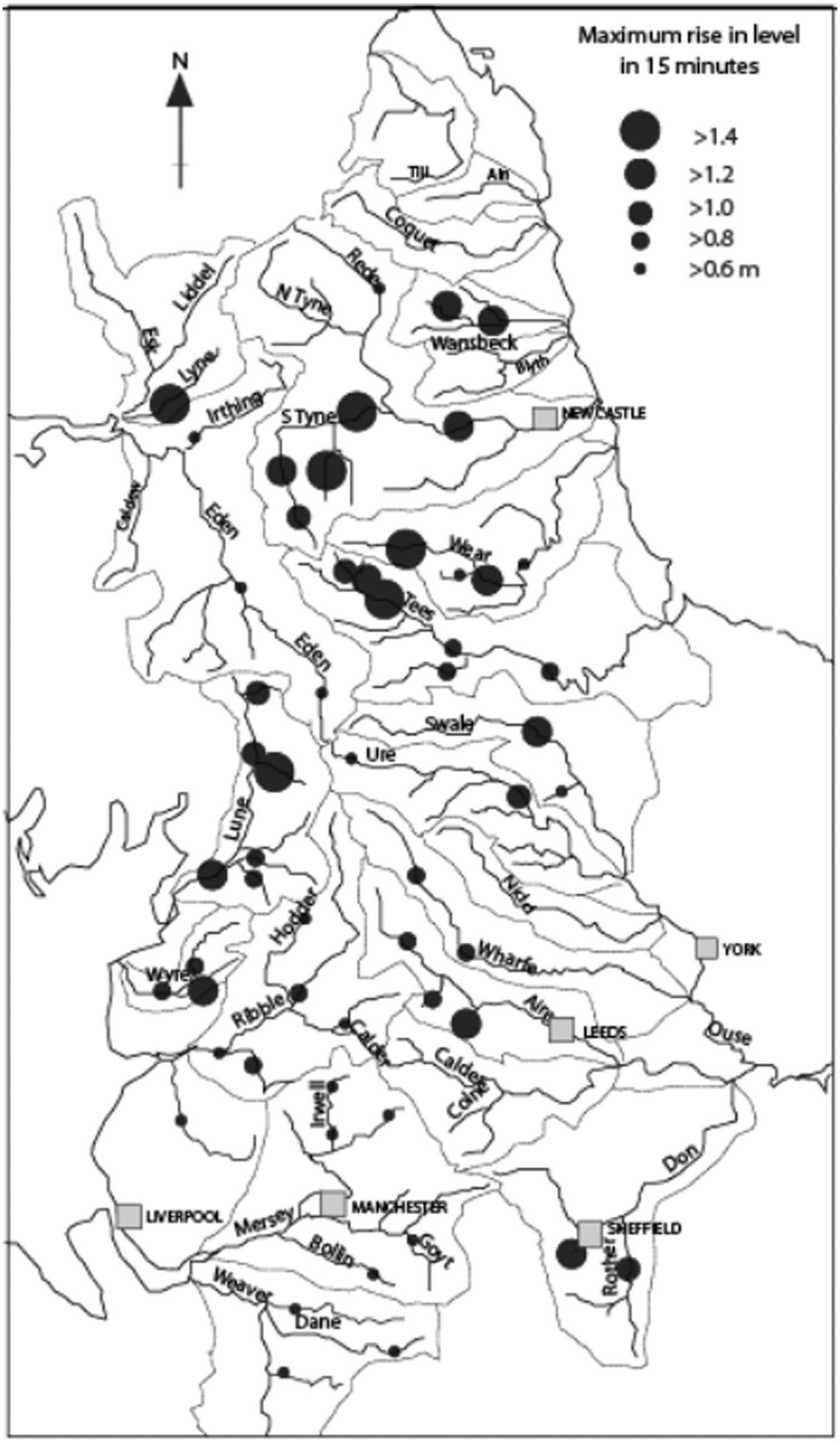

FIGURE 2 Maximum 15-min rise in level at Pennine gauging stations over the period of digital records, typically 1980–2014.

downstream with a steepening wave front over tens of kilometres. The occurrence of many such AWFs may also have gone unnoticed, for example, when they have occurred in uninhabited tributaries, at night, or have failed to be reported in the press if they did not cause damage to property or loss of life.

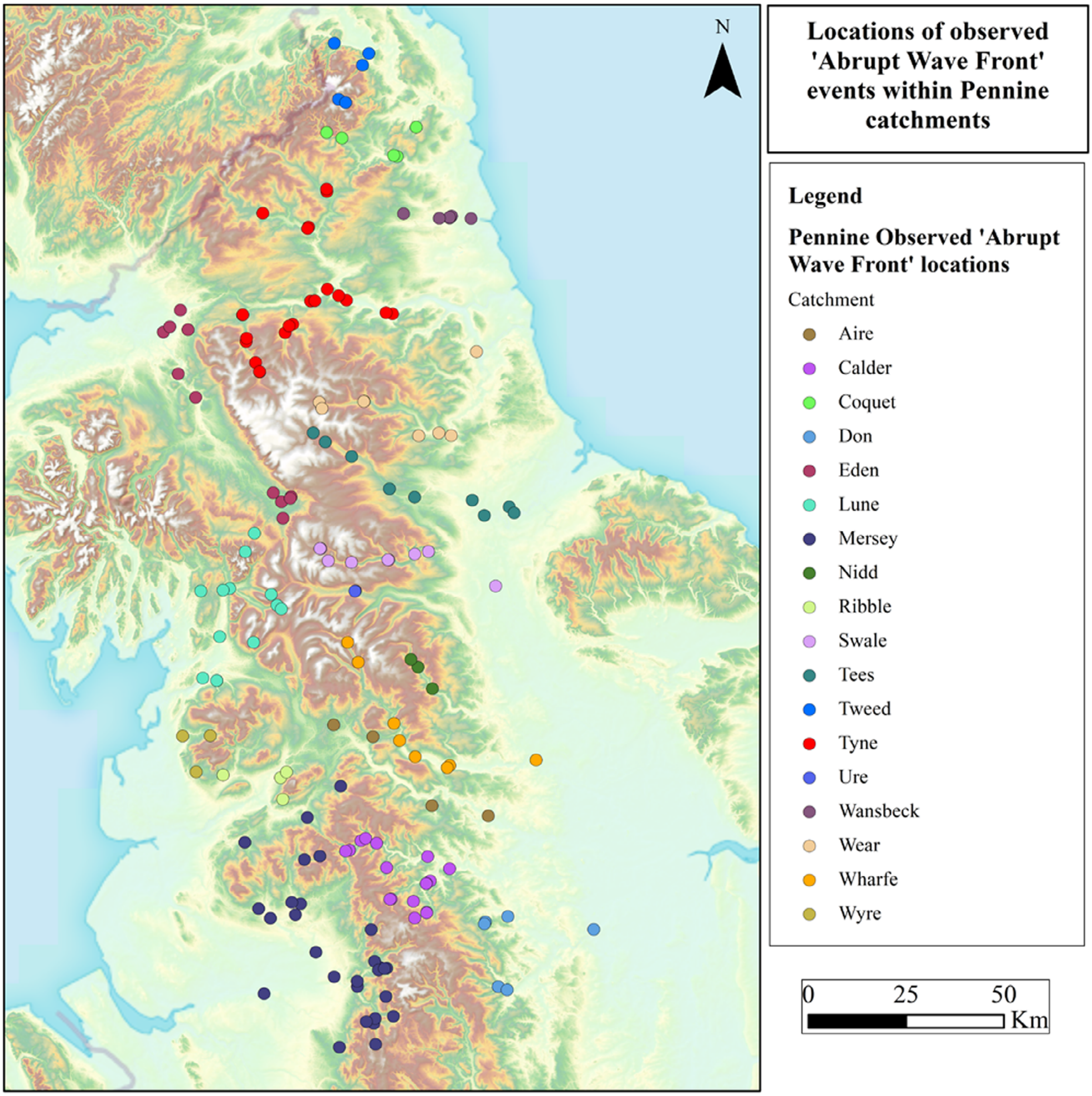

FIGURE 3 Locations of historical abrupt wave front floods (AWFs) on Pennine catchments (NB some events were observed at multiple locations and some locations had multiple events).

3 | ANALYSIS

3.1 | Comparison of AWF and normal flood hydrographs

That AWF are categorically different from normal floods is clearly illustrated in Figure 4, where the near instantaneous rise in level in AWFs is compared with the 'normal' gradual rise to peak for both winter and summer floods. The 15-min rise in level at the Stanhope gauging station on the River Wear on 7 June 1983 was 1.44 m, and on 17 July in the same year was 1.54 m. These events also affected the neighbouring River Tees (Watkiss & Archer, 2023). 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 within 24-h the level reduced to near the initial flow before the AWF. It was nearly 30 years before another 15-min rise exceeded 1 m; on 28 June 2012 the 15-min rise was 1.34 m. Unlike the 1983 floods, which were caused by very intense localised rainfall, pulses of convective rainfall in June 2012 were widespread in northern England, causing rapid rise in level in the northeast (Tyne, Wear and Tees) and as far south as

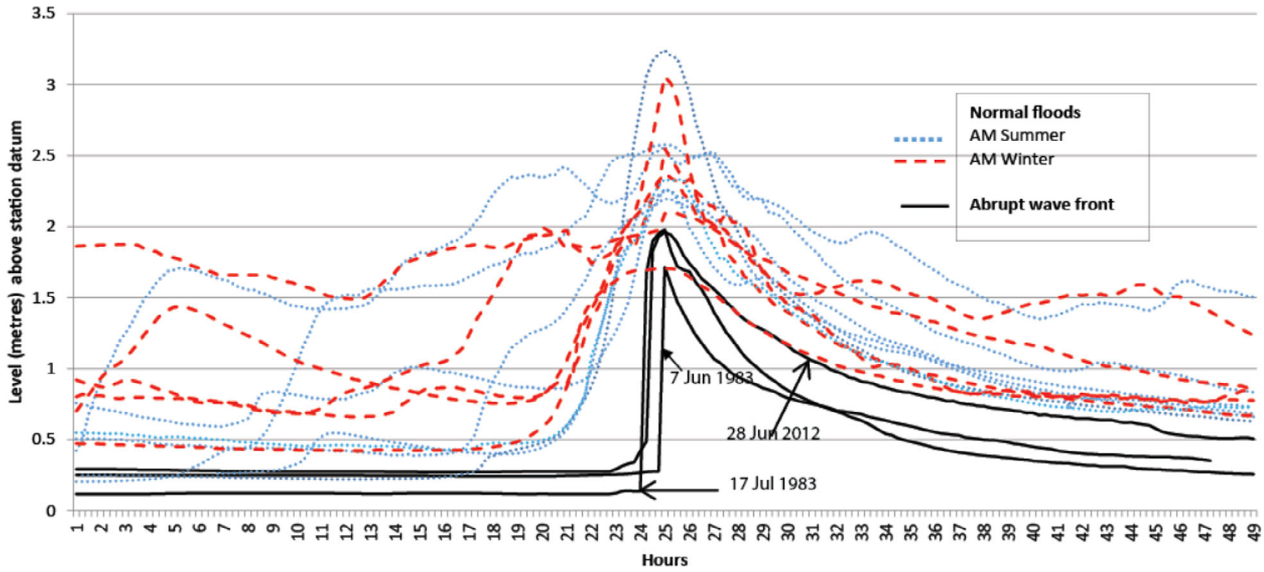

FIGURE 4 River Wear at Stanhope with flood hydrographs centred on the peak flow, showing the contrast between abrupt wave front floods (AWF) events (solid black lines) and all summer flow annual maxima (blue dotted lines) and the five winter flow annual maxima with highest peaks (red dashed lines).

rivers in Lancashire. Extreme surface water flooding occurred in Newcastle upon Tyne (Archer & Fowler, 2018). On the River Wear (Figure 4), the peak flow was still within 1 h of the rapid rise.

By contrast, the highest 15-min rise in (all) summer AM peak floods at Stanhope was 0.34 m on 13 May 2013 and, in the five largest AM winter floods, was 0.31 m on 3 January 1987. In each case normal flow rises from heavy persistent rainfall were preceded and followed by similar but smaller 15-min rises.

AM flood peaks were, with one exception, greater than the peaks of 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 safety risk and potentially risk to life posed by rate of rise.

3.2 | Assessing catchment vulnerability to AWFs

We now assess catchment vulnerability to AWFs by examining the attributes of a range of contributing Pennine catchments to historical AWF events, using the Flood Estimation Handbook (IH, 1999) catchment descriptors derived from the FEH Web Service. Data were extracted for all major Pennine catchments to include upland locations nearest to the point of generation (minimum area of 1.5 km^2) and those furthest downstream—representing the distance over which the AWF may be transmitted along the watercourse (maximum area of 1375 km^2). The points at which AWF were observed are often well downstream from the storm centre where they were generated; AWFs may continue downstream for tens of kilometres, as illustrated for the River Tyne (Archer & Fowler, 2018) and the River Tees (Watkiss & Archer, 2023).

FEH catchment attributes DPSBAR, DPLBAR, PROPWET, BFIHOST and SAAR were used to characterise the physical and climatological characteristics of AWF catchments. DPSBAR is a measure of mean catchment slope. BFIHOST uses the base flow index based on the Hydrology of Soil Types (HOST) soil classification and indicates the responsiveness of the catchment. DPLBAR reflects catchment size and drainage path configuration. PROPWET is the proportion of time the catchment soil moisture deficits are below 6 mm when catchment soils are 'wet', and SAAR (mm) is the catchment average annual rainfall from 1961 to 1990.

The same catchment descriptors were downloaded from the national dataset held on the FEH CD-ROM v1, filtered to Pennine AWF minimum and maximum of AREA (1.5–1375 km^2), ALTBAR (catchment mean altitude) (124–572 m) and SAAR (715–2023 mm). The national data set could not be filtered by region and therefore includes catchments outside of the Pennines. Figure 5 shows the distribution of AWF catchment descriptors plotted against the filtered national FEH dataset to determine whether catchments generating AWFs can be distinguished from similar (AREA, ALTBAR and SAAR) catchments. In addition, AWF catchments have

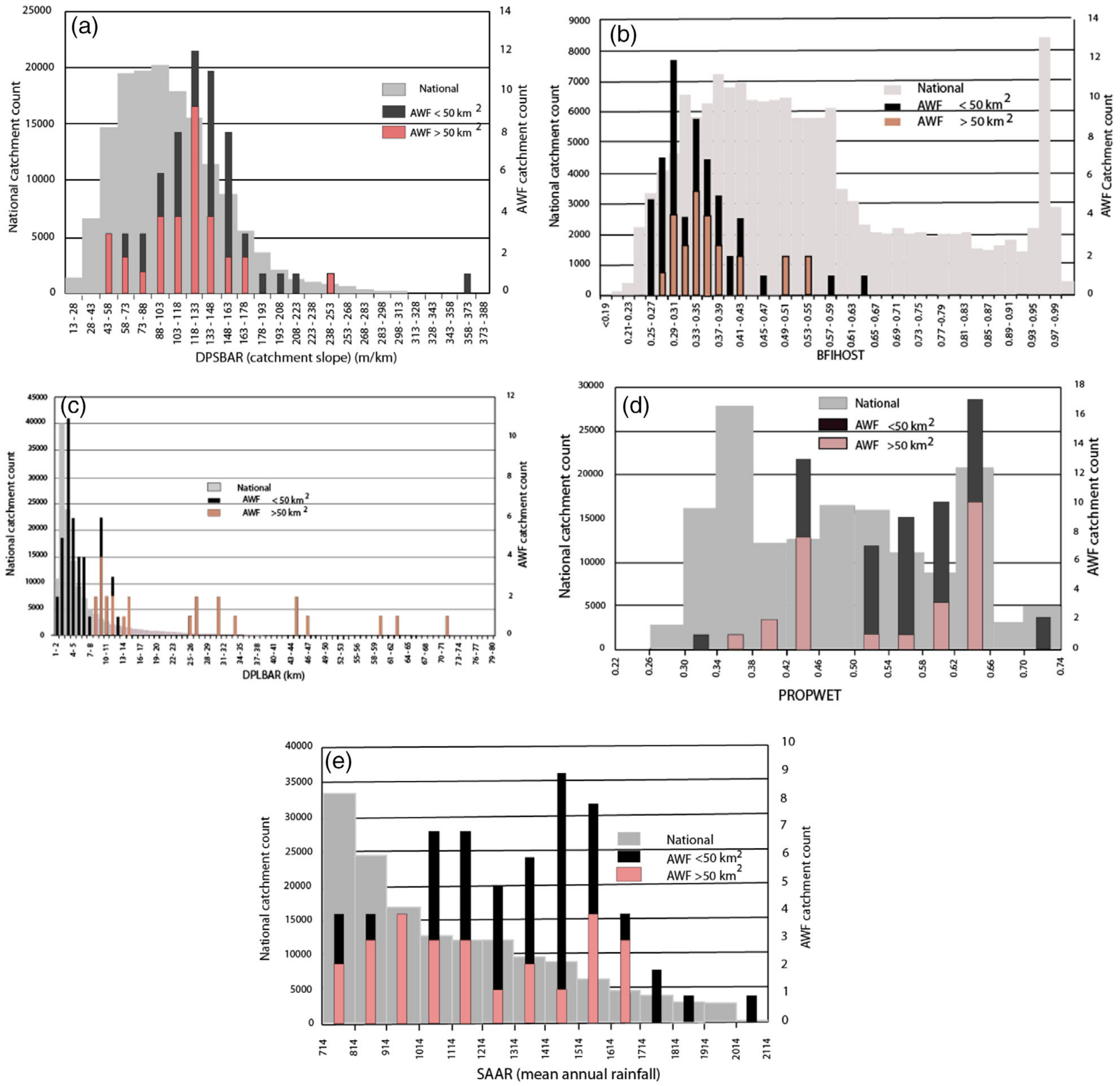

FIGURE 5 Distribution of abrupt wave front floods (AWF) catchments subdivided between catchments greater and less than 50 km^2 in area and compared with filtered 'national' catchments, with respect to (a) DPSBAR, (b) BFIHOST, (c) DPLBAR, (d) PROPWET and (e) SAAR.

been divided between those less than or greater than 50 km^2 (Figure 5a–e).

The analysis of DPSBAR confirms that AWFs originate predominantly on small, very steep, upland catchments (Figure 5a), on average ∼24 m km^{-1} steeper than the national dataset. DPSBAR for AWFs on catchments <50 km^2 averaged 142 m km^{-1} whereas catchments >50 km^2 averaged 116 m km^{-1}. The lowest AWF catchment slope was for the River Wansbeck (50 m km^{-1}) (Archer & Fowler, 2018). Such catchments are normally of low permeability, as illustrated in Figure 5b, with BFIHOST averages of 0.34 and 0.37 for catchments less than and greater than 50 km^2 respectively. For similar catchments from the national dataset, BFIHOST averaged 0.54. Exceptionally, the Silkstone Beck (Archer & Fowler, 2018), a tributary of the Dearne/Don with a catchment area of 6 km^2, has an unusually high permeability of 0.64. The DPLBAR values (Figure 5c) reflect the distance downstream that AWFs can be transmitted, with catchments in the north Pennines, Tyne, Tees and Eden experiencing AWFs at DPLBAR distances >60 km and for catchment areas >1000 km^2. PROPWET and SAAR demonstrate a general characteristic for AWF catchments of high annual rainfall and number of wet days, ensuring

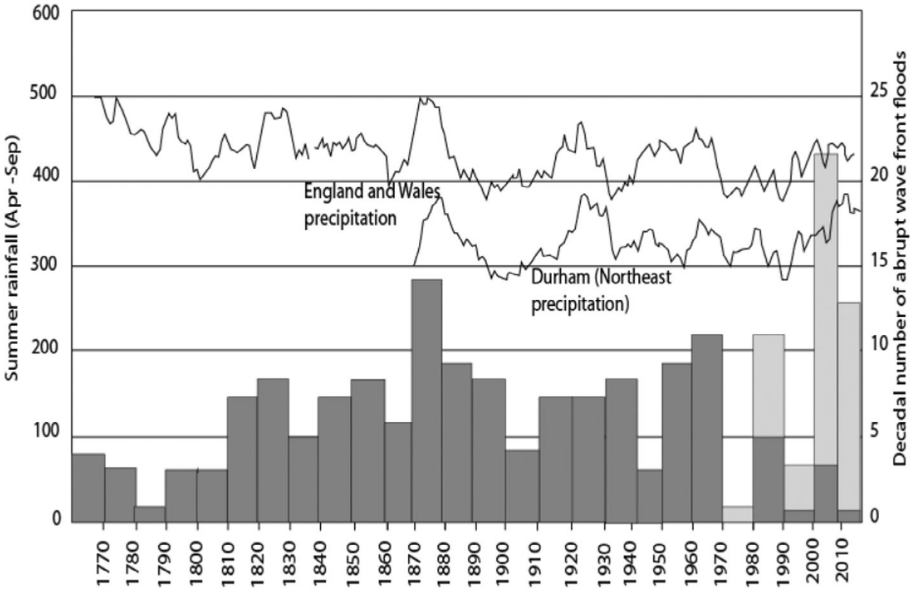

FIGURE 6 Decadal number of Pennine historical reported (dark grey) and gauged AWFs (light grey), and England and Wales summer (April to September) precipitation (10-year running means) (after Webster, 2021) for England and Wales and for Durham (representing northeast England).

frequently high levels of soil moisture, generally characteristic of upland locations. However, these conditions are not necessarily present at AWF initiation; these are often generated during storms following hot dry weather with antecedent low flows, as in examples for the River Wear (Figures 1 and 3). Viggiani (2020) notes that low base flow is a significant contributor to shock development in 'instant' floods as it influences the relative differences of wave celerity between initial flow and the AWF wave front. Similarly, Collischonn et al. (2017) states that the maximum increment in celerity due to an increment in discharge occurs at very low discharge values (low base flow conditions prior to the effective rainfall input).

Given the limited number and geographical range of AWF catchments included in the current analysis, the results do not yet provide a definitive basis for defining UK catchments vulnerable to AWF. Further work to use the entire national dataset of AWF contained in the flash flood chronology would provide a more reliable guide.

3.3 | Time series of AWFs

Climate model projections and observations indicate an intensification of precipitation with increase in temperature, according to the thermodynamic Clausius–Clapeyron (CC) relationship (a rate of $\sim$6%–7%°C^{-1})—a warmer atmosphere being capable of holding more moisture (Fowler et al., 2021). Moreover, analysis of hourly precipitation records (Ali et al., 2021) indicates that precipitation extremes can intensify with temperature at higher rates. Chapman et al. (2019) note, with reference to the Central England Temperature climate series, that heat wave activity has increased two- to three-fold since the late 1800s: the return period of a 6-day heat wave with a daily maximum temperature of at least 28°C has changed from about 6–8 years to about 2–4 years, about two to three times more frequent on average. Notably, Sauter et al. (2023) also find a strong link between heatwaves and following extreme short-duration rainfall across much of the mid-latitudes, including the UK, with some regions showing substantial increases in extreme rainfall events after heatwaves, multiple factors above climatology.

One might therefore expect a recent increasing prevalence of intense rainfall events causing AWF floods. However, based on newspaper and professional reports, the decadal occurrence of AWF over the last 50 years is lower than over the previous 200-year period (Figure 6). Gauged records of rate of rise in Pennine catchments do show additional events where the water has risen abruptly from a low level by more than 0.6 m between 15-min observations, but few over 1 metre. These have rarely received any press description or even have rainfall records. It is likely that many events during the historical period have also been unrecorded; only those major events which have caused loss of life or a threat to life have been reported in the press.

The time series of historical AWFs on the Pennines (Figure 6), indicates high numbers through most of the nineteenth century especially after 1870; then a decline to low numbers from 1900 to 1910, and rising again to higher levels from 1930 to 1970, before the recent decline. Foulds and Macklin (2015) note a very similar pattern of time variation in upland channel-forming floods in England and Wales using lichen-dated boulder-berms including high late 19th century frequency, a dip after 1900, rising again until 1950 and the recent decline. It may seem anomalous

TABLE 2 Contrasts in properties of gauged 15-min rise in Northern and Southern Pennine catchments.

River	Station	Maximum 15-min rise in level (m)	Median AM 15-min rise in level (m)	Maximum 15-min rise in flow ($m^3 s^{-1}$)	Median AM 15-min rise in flow ($m^3 s^{-1}$)	Catchment area (km^2)
Tyne	Haydon Br 1975–2015	1.49	0.81	171	126	751
Wear	Stanhope 1982–2014	1.54	0.68	79	27	172
Tees	Middleton 1982–2014	1.53	0.82	148	55	242
Mersey/ Goyt	Marple Br 1969–2014	0.74	0.21	7.2	2.3	183
Calder	Elland 1966–2014	0.315	0.145	25.5	13.5	341

that more frequent AWF events have occurred in a historic period of lower summer temperatures.

Several potential climatological and catchment changes have been investigated for this puzzling observed pattern of occurrence. Whilst summer temperatures were lower, the end of the nineteenth century was a period when summer rainfall was more than 10% higher than at present in both the England and Wales series (Gregory et al., 1991; Webster, 2021) and mirrored at Durham, a long record representing northeast England (Figure 6) (https://durhamweather.webspace.durham.ac.uk/open-access-climate-datasets/). Although seasonal summer rainfall does not necessarily coincide with more frequent or extreme rainfall, it may form a platform of higher soil moisture from which runoff from high rainfall may more readily translate into flash floods and abrupt wave fronts.

Further potential explanations emerge from the comparison of northern (Tyne, Wear and Tees) and southern (Mersey and Calder) Pennine catchments for historical and recent gauged AWFs. A similar number of historical AWFs were noted for the northern Pennine catchments of the Tyne, Wear and Tees as for the southern catchments of the Calder and Mersey. However, for recent digital data, the northern Pennine catchments had multiple occurrences at several locations of 15-min rises >1 m, whilst the Mersey and the Calder had none. Table 2 shows a comparison of the maximum and median AM 15-min rise in level and discharge for northern and southern catchments. The recent gauged data indicate that southern catchments show much lower rates than northern catchments.

Historical floods of great severity did occur on both southern rivers. For example, on the Goyt/Mersey, in a flood in 1748, mills, bridges and houses were destroyed and two women were swept away and drowned, and at Marple Bridge, the water was reported to rise over the parapets to a height of 22 ft (6.71 m) above its ordinary level. Severe AWFs occurred on Mersey tributaries in 1870 (Irwell), 1872 (Bollin), 1881 (Goyt) and 1884 (Irwell and Goyt). On the Calder and its tributaries, extreme AWF floods were reported in 1768, 1777, 1822, 1870, and most recently in 1944 (Archer & Fowler, 2021). The occurrence of past extreme floods in the southern catchments contrasts with the recent difference in median AM 15-min rise, where southern catchments show much lower rates than northern catchments. There are two potential explanations.

1. The headwaters of the Mersey and Calder catchments are heavily reservoired. The Calder at Elland is 15.4% reservoired and the Goyt at Marple Bridge 32%. The reservoirs are on upland tributaries where AWFs are usually generated and are generally drawn-down during summer months when intense rainfall occurs. Flood flows initiated by typical AWFs could often be contained and not transmitted downstream. Smaller reservoirs were constructed in the nineteenth century but larger storages have been constructed since 1900. In contrast, the River South Tyne is unreservoired and recent AWF floods on the Wear and Tees have originated on tributaries without reservoirs.
2. The cotton and woollen industries of Lancashire and Yorkshire were powered by water on upland streams

with weirs and mills close to the river where they were vulnerable to flooding. Many historical accounts of flash floods refer to the damage and destruction of such mills and weirs, possibly of smaller magnitude than would cause such damage to present infrastructure. Severe effects of such events were also likely to be reported in newspapers. This could provide a partial explanation of the high levels of reported AWFs on the Calder and Mersey catchments in the late nineteenth century.

Given the correspondence between rainfall and AWF series an explanation based on climate seems likely but does not explain the decline in the reported number of AWFs in the late 20th century in newspapers. Foulds and Macklin (2015) suggest that a similar time series of floods dated by lichenometry from upland erosion have been triggered by torrential summer downpours related to a marked negative phase of the summer North Atlantic Oscillation (NAO). This is not further considered in this paper. The frequency of AWFs on the Mersey and Calder must also be diminished by the influence of upland reservoirs and by less frequent reporting of such events on catchments where the infrastructure is no longer vulnerable.

4 | DISCUSSION

We focus here on two practical issues with respect to the provision of a forecasting and warning service for AWFs: the development of appropriate means of monitoring, and modelling the occurrence of AWFs.

4.1 | AWF monitoring

Intense rainfall in the headwaters of catchments usually causes rapid rise in river level but rainfall measurement is sparse or absent, for example, for the event in June 1983 on the River Wear (Figure 2). Even when rain gauges are present, the high spatial variability of storm rainfall (Archer & Wheeler, 1991) makes estimation of mean or maximum rainfall and the timing uncertain. Rainfall radar estimates provide the best basis for estimation but these are dogged by the occurrence of 'bright band' overestimation, with the occurrence of melting hail (Lin et al., 2020). In addition, there are uncertainties in the accuracy of estimates in the most intense rainfall due to attenuation (Thompson et al., 2011) or the failure to account for natural variations in raindrop size distribution with intensity (Schleiss et al., 2020), usually resulting in underestimation.

Similarly, present measurement of river levels does not provide a reliable basis for understanding of AWFs or for operational response. Since the advent of punched tape recorders in Britain in the 1960s, the standard interval of level measurement has been 15-min and this has continued with replacement by digital recorders, although some installations are capable of higher-resolution sampling. For events described as AWFs, it is unclear whether the rise is distributed equally over the 15-min or whether it occurred nearly instantaneously. In addition, in some AWF events the wave front and peak may have passed between the start of the rise and the subsequent measurement so that the recorded peak falls on the recession and thus underestimates the actual peak. Examples are shown in Figure 1 for an event occurring simultaneously on the Rivers Wear and Tees on 6 June 1983. In each case, changes may be further subdued by stilling well lag (Herschy, 1995).

Given the experience with events on the River Tyne (noted above), it is suspected that velocities and discharge during AWFs do not correspond with the established rating curve; velocities could be much higher for a given level. Providing evidence for this is more difficult than for level. Perhaps the best opportunity for this is by using cross channel ultrasonic recorders which make continuous velocity measurements. These are currently averaged over a 15-min period but the instrument software provides for recording at 1-min intervals. On vulnerable catchments, such as the Tyne and Tees, it is recommended that a similar reduced interval be applied. However, even ultrasonic recorders have difficulty in maintaining the record in the presence of high suspended load or the turbulence typical of AWFs (https://nrfa.ceh.ac.uk/how-are-flows-measured).

It is recommended that in vulnerable catchments the logger software is modified to reduce the interval of level measurement to 1-, 3- or 5-min (factors of 15-min) to establish whether the AWF occurred as a near-instantaneous wave or more gradually over the 15-min interval. It is recognised that these AWF events are quite infrequent, only recorded once a decade on some catchments. It is further recommended that monthly and annual statistics of level and discharge rise for intervals from 15-min to 2-h (and < 15-min when available) should be extracted and archived for all stations in the UK network as a basis for identification of AWFs and the analysis of rate of rise statistics.

4.2 | Modelling of AWF for risk assessment

Models commonly applied in the UK for design floods (IH, 1999) primarily estimate the risk of peak discharge and flood volume but do not adequately address the risk of very rapid rates of rise as AWFs. The Flood Estimation Handbook rainfall-runoff method in the UK (IH, 1999; Kjeldsen et al., 2005) provides a means of creating a design storm hydrograph from rainfall of given return period and duration occurring over the entire catchment. A fixed time to peak (Tp) parameter establishes a standard unit hydrograph and the associated steepness of the rising limb for each catchment based on uniform rainfall over the entire watershed (Sherman, 1942). The simple properties of the unit hydrograph assist in its application, but the assumption of uniform catchment rainfall, and a centred storm profile, has limited applicability for AWFs where rainfall is usually localised and of high and variable intensity. Real storms, especially short-duration ones, tend to be front-loaded, suggesting the need for new design rainfall profiles to address the risk of rapid rates of rise (as discussed by Villalobos-Herrera et al., 2023).

Similarly, the concept of linearity (that 20 mm effective rain produces double the flow of 10 mm effective rain) has long been identified as a serious limitation for consistent application for design risk (e.g., Chow, 1964). Attempts to define the variation in Tp in terms of mean rainfall intensity (NERC, 1975) or event peak magnitude (Ashfaq & Webster, 2000; Kjeldsen et al., 2005) have proved inconclusive. However, evidence from recent events, including the extreme flood at Helmsley in 1975 on the River Rye, where the lag time was only one third of the average for other floods (Wass et al., 2008), provides clear evidence that the critical influence on Tp is not mean rainfall intensity but maximum short-period intensity.

Risk management authorities in the UK have also used a unit hydrograph approach to identify the risk of floods that occur suddenly as part of the screening methods to produce a register of ‘Rapid Response Catchments’ (RRCs) (Francis, 2010). The unpublished methodology uses estimates of a characteristic unit hydrograph of catchments with Tp <3 h, along with estimates of the depth, velocity and risk to people of the potential peak flood flows, based on research published by Defra and Environment Agency (2006).

Although there is some overlap between RRCs and catchments on which AWFs occur, they address different aspects of hazard. For AWFs, the average Tp of a catchment is largely irrelevant (and in any case is variable with rainfall intensity as noted above). AWFs may occur on catchments as large as the Tyne at Bywell, with a catchment area of >2000 km^2 and Tp >8 h. Instead, it is the ‘threat response time’ (Archer & Fowler, 2018) which is critical. Many Pennine catchments on which AWFs have been observed are not, by definition, RRCs but experience, by exception, rapid response events (Watkiss & Archer, 2023). In the absence of an intense rainfall forecast, the threat response time may be less than a minute for in-river users overtaken by such abrupt wave fronts.

Models routinely used for flood estimation and forecasting, for example, PDM (Moore, 2007) or TOPMODEL (Beven et al., 2021), have not been shown to generate a rapid rise in discharge. Hydrodynamic models capable of simulating AWFs now exist, e.g. CityCat (Glenis et al., 2018), but are yet to be used for forecasting. In the absence of this, the best approach to identifying vulnerable catchments is through the identification of the catchment characteristics on which AWFs have historically occurred and which support AWFs through historical and recent observations (as demonstrated above). This can then be used as an analogue for hydrologically-similar catchments on which AWFs have not yet occurred.

4.3 | Modelling of AWF events for forecasting and warning

AWF events typically originate from intense short period rainfall on small, steep, upland catchments and may be transmitted downstream in the main river for tens of kilometres. Such events may require a staged approach to forecasting or measuring (i) the rainfall source, (ii) the creation of the headwater flood and (iii) the development and transmission of the flood wave downstream.

At the upstream source, AWFs pose a significant challenge for hydrological models. Additionally, small, steep headwater catchments that are likely to respond quickly to storms are often not gauged for rainfall or flow, and so even hydrodynamic models may not be easily set-up. However, for intense short period rainfall, weather forecasts provide the dominant uncertainty, with high uncertainty in both the location and intensity of forecast rainfall. Thus, it may be more practical to use the rapidly rising level in the headwaters of the main stem of the river to provide advance warning, and to then model the propagation and timing of the steepening wave downstream with a hydrodynamic model. Forecasting the wave front is more important on those Pennine rivers where the wave progresses far downstream and the risk to life of river users is greatest.

It may be informative at this point to reflect on the representation of key controls on AWFs in theoretical models. Viggiani (2020) analysed the physical mechanism of development and propagation of surge waves (equivalent to AWF) or ‘instant floods’, with faster evolution than common flash floods. Differences in wave celerity are recognised as the basis for surge wave development, so that there is a tendency for the rising limb of the hydrograph to steepen because higher flows correspond to deeper and faster waves. However, this only occurs under favourable conditions of flood initiation and channel morphology, including high channel slope, abrupt lateral inflow, low initial flow, and particular channel cross-section shape. Huang and Lee (2020) add roughness as a contributing factor. Viggiani (2020) carried out numerical tests of the influence of these channel and flow conditions using the complete form of the unsteady flow equations. He concluded that canyon and mountain streams with steep sides are potential sites for surge wave development or appreciable hydrograph steepening, successfully demonstrating the application of numerical models to simulate instant flow propagation in a steep natural stream similar to Pennine headwaters. Results show a significant steepening of the rising limb, creating an AWF with rise of over 1 metre ($m^3 s^{-1}$) only 12 s after wave arrival.

We recommend that example AWF events are simulated, where hydrodynamic models designed to represent the propagation of rapid rates of rise, could be tested. These might include events on the River Tyne on 30 July 2002 (Archer & Fowler, 2018) and 19 July 2007 (Archer & Fowler, 2021), where AWF hydrographs were measured at four successive gauging stations and reported by observers as 'walls of water'. It is also recommended that flood risk models be designed or adapted to simulate such a sudden rise in level for design flood estimation and forecasting.

5 | CONCLUSIONS

1. Occurrences of AWFs are investigated using both qualitative historical information starting from the eighteenth century and quantitative gauged data from all digital records of level in the Pennines of northern England.
2. Evidence is provided to show that AWFs can be generated by extreme short period rainfall and do not require the occurrence of upstream blockage.
3. Analysis of catchment descriptors (Figure 5) can provide a basis for defining those catchments at greatest risk and then used as a focus for forecasting.
4. AWFs originate in steep upland tributaries, usually with a catchment area less than 50 km^2 (Figure 5a) but can progress downstream in some Pennine rivers for many tens of kilometres (Figure 5c) and to catchments greater than 1000 km^2.
5. AWFs are a hazard for river users quite separate from the magnitude of the flood peak, arising from a combination of rapid rise in level, velocity, and the impact of the wave front. AWFs rarely correspond with the highest observed flood levels.
6. AWFs have occurred in every major river system in the Pennines in northern England, as shown both by historical and recent digital data. The most severe recent events have been in the northern Pennines (Tyne, Wear and Tees). Historically clusters of events have been severe in both the northern and southern Pennines (Calder and Mersey).
7. AWFs show a sharp increase in number from the mid- to late-nineteenth century, a decline from 1900, rising again to higher levels from 1930 to 1970, but fewer in number in recent decades. The timing shows correspondence with time series of summer total precipitation.
8. Current monitoring of intense rainfall, river levels and velocity do not provide a reliable basis for understanding AWF processes or for operational response. The principal suggestion is to reduce the interval of level measurement from 15 minutes to 1 minute on vulnerable catchments.
9. It is recommended that models used operationally for forecasting be augmented by new hydrodynamic modelling approaches that can well-simulate these AWF events and these can be tested against historic events.

ACKNOWLEDGEMENTS

Initial data extraction of rate of rise data for all British gauging stations formed a part of the research for the SINATRA project supported by the United Kingdom NERC Flooding from Intense Rainfall programme (grant NE/K00896X/1). Data analysis and catchment descriptor acquisition by SW and SW was supported by JBA Trust project W20-3873. The remaining research was unfunded.

DATA AVAILABILITY STATEMENT

I confirm that I have included a citation for available data in my references section and added Supplementary Information.

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How to cite this article: Archer, D., Watkiss, S., Warren, S., Lamb, R., & Fowler, H. J. (2024). Gauged and historical abrupt wave front floods ('walls of water') in Pennine rivers, northern England. *Journal of Flood Risk Management*, e12989. https://doi.org/10.1111/jfr3.12989