Abstract
The chronology provides a record of flash flood events in Britain based on data collated mainly between 1700 and 2020. The primary purpose of the chronology is to improve the risk assessment of flash floods of given magnitude. It is divided into 18 regions of the country and contains descriptions of nearly 8000 events. It extends a previous chronology covering northern and southwest England which is provided as an online resource in (http://ceg-fepsys.ncl.ac.uk/outputs/). Flash floods have had a variety of previous definitions but are here defined in terms of the speed of onset which can apply to both river floods and surface water floods. The chronology for the first time provides a comprehensive list of surface water floods and their recorded impact on cities, towns and villages. It also draws attention to the prevalence of very rapid rates of rise in river level either as ‘walls of water’, or at a rate likely to endanger life as a result of intense rainfall. Nearly 300 such events have been identified mainly in upland areas of northern England, Wales and Scotland. Practical and theoretical issues with respect to flood risk assessment and warning are discussed. The chronology 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/

KEYWORDS
chronology, flash flood, hail, intense rainfall, rate of rise, surface water flood

1 | INTRODUCTION

Flash floods, like all natural hazards, require historical information to enable comparison between events and to assess risks of future occurrence. Such information is widely available for river floods in the form of measured peak river levels and discharges in Britain in the National River Flow Archive (NRFA; https://nrfa.ceh.ac.uk/peak-flow-data) and also for historical reports and observations as described by Black and Law (2004) in the Chronology of Hydrological Events. However, flash floods, as defined below, have limited and widely dispersed recent observations and therefore historical evidence in the form of a chronology is particularly important in assessing current risks and the patterns of occurrence at specific locations.

Flash floods are a subset of floods in general but with a wide range of definitions and an uncertain boundary with ‘normal floods’. It is therefore necessary to consider the various definitions that have previously been applied and the reasons for differing usage, either for individual floods or for flash flood chronologies, as a basis for the format and content of the British flash flood chronology described here.
Kobiyma and Goerl (2007) list 16 definitions, mainly from international and American agencies (not necessarily for chronologies). The definitions are all with respect to river floods and do not refer to flooding from surface water (before rainfall reaches a watercourse). Seven of these note that the lag time between the causative rainfall and the occurrence of the flood is a defining feature of flash floods. The lag is said to be ‘short’ or in some cases limited to a specified time, typically 6 h (National Disaster Education Coalition, 2004; WMO, 1994). Seven definitions also note the occurrence of a rapid rise in water level but none actually specify a limiting rate of rise between a normal flood and a flash flood; one definition notes the possible occurrence of a ‘wall of water’ (Federal Emergency Management Agency, 1981). Several indicate that flash floods occur in steep slope regions (Castro, 1996) or occur over a small area, for example, Kelsch (2001) analysed 22 flash floods in the United States with an average catchment area of 46 km². The Environment Agency (2009) defines it very generally as ‘a localised flood with very high volumes of fast-flowing water, often carrying large debris, that rises very quickly, with an immediate threat to life’ Kobiyma and Goerl (2007) propose the use of the Operation Efficiency Index (OEI) as a quantitative means to distinguish between a normal flood and flash flood event. The OEI is defined as the rate of the time of flood concentration (Tc) to the operational response time (To). A flash flood is distinguished from a normal flood when the OEI value is smaller than one. Similarly, Borga (2014) suggests a flash flood as a flood where the time for the development of the flood from the upstream catchment is less than the time needed to activate warning or defence measures downstream.

Chronologies or databases of flash floods also suffer from a wide variety of definitions. Kaiser, Gunnemann, and Disse (2020) described 11 chronologies, 5 from Europe, 3 from the United States and 1 from China. The majority of these used properties of rainfall as the principal factor to define a threshold between flash floods and normal floods (between short intense or long-lasting precipitation). However the chronologies use very different properties, said to be the result of strong regional dependencies which make thresholds difficult to define. In southern Europe, studies of individual flash floods have mainly been defined by extreme rainfall totals and peak discharges (e.g., Huet et al., 2003; Lefrou et al., 2000). Gaume et al. (2009) compiled an inventory of 550 extreme flash floods in seven countries in Europe. Events were defined in terms of peak discharge, with rainfall duration less than 24 h and on catchments generally less than 500 km². However, it is not clear how the selected events differed categorically from large ‘normal’ floods. The European Severe Weather Database dataset (ESWD, 2017) uses heavy precipitation events lasting between 30 min and 24 h and applies the following as the precipitation threshold:

\[ P \geq 2 \sqrt{5t} \]  

where \( P \) is the precipitation amount in mm and \( t \) is the duration in minutes.

Other chronologies do not specify a minimum rainfall amount but limit the duration of intense rainfall, for example, <6 h for the Chinese database of He et al. (2018), <24 h for the European HYDRATE database (Borga, Anagnostou, Bloschl, & Creutin, 2011) and <48 h for the Mediterranean EuroMedeFF database (Amponsah et al., 2018). Upper thresholds of catchment size also vary between datasets, from <50 km² (URBAS dataset, Einfalt et al. (2009) for German urban catchments only), to <3000 km² in the EuroMedeFF database. Douvinet and Delahaye (2010) described flash floods (‘crues rapides’) on the plateaus of north-western France, with many of the 269 compiled events occurring in dry valleys and they specifically referred to the speed of onset and the intensity of short-period rainfall (<1 h). With respect to river flows this is closest to our definition described below.

However definitions also vary with respect to intended usage. Recent datasets with comprehensive spatial information on rainfall intensities have served as a basis for verification of flood forecasts, for example, the Storm Events Database – a 4-year record for events in the United States. The HYDRATE and EuroMedeFF databases are used to model flood hydrographs and peak discharges. But most are used primarily to improve flood risk assessments given the short length of recent comprehensive event descriptions.

### 2 | Definition and Purpose of the British Flash Flood Chronology

Given the variety of definitions for flash floods in the literature, a statement of the definition used in the accompanying chronology is necessary. This can be then be used to give a context to the content and purposes of the chronology. The use of the word ‘flash’ assumes a sudden or rapid onset which provides a different and additional flood hazard to the maximum flood level. Rapid onset or rapid rate of rise in level and discharge can therefore be considered the principal defining feature to distinguish from ‘normal’ floods and can equally be applied to river floods as to surface water or pluvial floods. Archer and Fowler (2018) propose a defining factor to be a ‘threat response time’: the time from the initial perception of a flood (by a victim) to the occurrence of a level posing a
threat to life and property. Threat response times may be nearly instantaneous and are typically measured in minutes in the most serious flash floods. In the absence of specific information on response times, the rapidity of flood onset is often described by victims as providing insufficient time to take remedial action with respect to protection of goods and property.

With rapid response as the primary defining factor, there is no need for a defining rainfall amount or maximum (or minimum) duration. A maximum lag time between the occurrence of rainfall and the ensuing flood peak is inappropriate; a river flash flood with rapid rise in water level generated in the headwaters may be transmitted downstream and pose a threat to river users several hours later (Archer & Fowler, 2018). The widespread use of a measure of fixed catchment lag (time of concentration: time to peak of unit hydrograph [UH], etc.) is also problematic since there is strong evidence that lag time is very much reduced on certain catchments when short-term rainfall is sufficiently intense (Archer & Fowler, 2018; Wass, Lindsay, & Faulkner, 2008). The definition by Borga (2014) decouples the concept of flash floods from any definition based on flood lag time, but like Kobiyama and Goerl (2007) his definition of a flash flood depends on the reaction time of a flood warning system, which can hardly be applied to historical floods before operational response measures were in place. Similarly, a maximum area is not required; urban flash floods may cover just a few hectares whilst river flash floods may occur on catchments over 2000 km² in area (Archer & Fowler, 2018). However, where available, rainfall amounts or intensities and the area and other catchment characteristics of river flash floods provide an essential backdrop to the event description.

The primary purpose of the chronology is to improve the risk assessment of flash floods of given magnitude for a given location and more generally of catchment vulnerability. Flash floods arising from intense rainfall are rare events at a particular location and there may be few if any recent records. A search of a chronology of more than 200 years provides a better basis for assessing the probability of occurrence (Archer, Parkin, & Fowler, 2017), than the limited observations currently available. Hence, remedial measures can be carried out with greater confidence and lower costs.

### 3 Description of the Chronology

The chronology was initiated as part of the SINATRA project which was supported by the United Kingdom NERC Flooding from Intense Rainfall programme (the ‘early chronology’). Chronologies were prepared for northern England and southwest England (Devon and Cornwall) divided into eight ‘regions’, as shown in Figure 1 and described in Archer, O’Donnell, Lamb, Warren, and Fowler (2018) and provided as an online resource in (http://ceg-fepsys.ncl.ac.uk/fc).

The interest shown by users provided the stimulus to extend the chronology to the whole of Britain, including Scotland and Wales (but not Northern Ireland), as a private project by the first author, in part supported by residual funds in SINATRA. The ‘extended chronology’ is divided between a further eight regions shown in Figure 1. The decadal number of events by region is shown in Table 1, with a total number of events for all regions of 7941.

The flood chronology is provided as a summary text description of each event in a Microsoft Word document in a three-column table. The first column gives the date of the event with the source(s) of the information (including newspaper dates). The second column gives associated meteorological information, mainly from British Rainfall (1861–1961) and Climatological Observers Link (1970–2019) but occasionally from other sources. Short period rainfall amounts are especially noted, but daily rainfall totals are also listed, especially in the early chronology where these might have included descriptions of short bursts of high intensity. The third column contains descriptive information, notably locations which were flooded and the depth and extent of flooding. Collated information includes flood deaths, destroyed bridges, flooded area, depths in named buildings, roads flooded, flood pathways in settlements and rural erosion. The impact and potential impact of hail on flooding are also included.

#### 3.1 Sources of information

The main source of information for the extended chronology is the British Newspaper Archive (BNA), an online source which can be searched by date, location, newspaper and by the use of selective words (https://www.britishnewspaperarchive.co.uk/). At the beginning of the search in 2012 for the early chronology the archive contained 12 million pages but by the end of 2019 when the search was completed the total number of pages had increased to 35 million. The BNA has been searched year by year from April to October from the beginning of the archive in 1700 using the words ‘flood’ and ‘thunder’ as a means of identifying potential flash flood occurrence. The limitation to the months from April to October is justified by reference to the British Rainfall record of ‘intense rainfall in short periods’ where less than 2% of
such reported occurrences are outside this period. Einfalt et al. (2009) also limit their urban flash flood chronology (URBAS) to the period April to October.

The BNA record becomes sparse after 1960 and alternative sources were sought to cover the period to the present. For the early chronology, the gap was filled by visits to libraries and Local Record Offices in the selected regions to collect data from hardcopy recent regional and local newspapers. It was not considered practical to access such information for the extended chronology due to...
| Decade | Northumbria | Swale | N York Moors | S Yorks | Lancashire | Eden | West Lakes | South Lakes | Southwest 1 | Scotland | Trent | East Anglia | Thames | Southeast | Southwest 2 | Severn | Wales | Total |
|--------|-------------|-------|--------------|---------|-------------|------|------------|------------|-------------|-----------|--------|------------|--------|-----------|------------|--------|-------|-------|
| <1700  | 3           | 4     | 0            | 8       | 4           | 2    | 0          | 6          | 12          | 1         | 2      | 9          | 6      | 1         | 0          | 2      | 2     | 62    |
| 1700–1750 | 4          | 2     | 3            | 9       | 2           | 0    | 1          | 2          | 1           | 4         | 11     | 3          | 7      | 3         | 8          | 8      | 2     | 70    |
| 1750–1770 | 3          | 1     | 1            | 0       | 0           | 1    | 2          | 0          | 5           | 0         | 2      | 2          | 4      | 2         | 3          | 1      | 1     | 29    |
| 1770–1780 | 5          | 0     | 1            | 8       | 3           | 1    | 2          | 1          | 6           | 5         | 2      | 3          | 5      | 5         | 4          | 4      | 2     | 57    |
| 1780–1790 | 4          | 1     | 0            | 2       | 1           | 2    | 0          | 3          | 2           | 2         | 1      | 2          | 0      | 3         | 0          | 1      | 0     | 24    |
| 1790–1800 | 6          | 0     | 0            | 6       | 6           | 4    | 2          | 4          | 5           | 6         | 2      | 5          | 5      | 5         | 1          | 3      | 5     | 55    |
| 1800–1810 | 2          | 1     | 0            | 9       | 4           | 4    | 3          | 3          | 2           | 2         | 8      | 3          | 0      | 1         | 0          | 2      | 4     | 46    |
| 1810–1820 | 4          | 0     | 1            | 5       | 8           | 4    | 3          | 2          | 6           | 13        | 4      | 5          | 4      | 3         | 4          | 4      | 2     | 80    |
| 1820–1830 | 6          | 3     | 1            | 13      | 9           | 6    | 8          | 6          | 6           | 12        | 6      | 16         | 8      | 8         | 5          | 6      | 4     | 123   |
| 1830–1840 | 12         | 2     | 4            | 20      | 20          | 7    | 9          | 11         | 6           | 18        | 10     | 8          | 10     | 5         | 3          | 9      | 6     | 160   |
| 1840–1850 | 15         | 1     | 3            | 14      | 19          | 9    | 7          | 7          | 18          | 15        | 8      | 12         | 15     | 11        | 5          | 15     | 12    | 186   |
| 1850–1860 | 10         | 1     | 6            | 27      | 38          | 9    | 10         | 10         | 22          | 21        | 20     | 23         | 19      | 18        | 15         | 18     | 9     | 276   |
| 1860–1870 | 14         | 3     | 8            | 29      | 28          | 12   | 8          | 11         | 16          | 22        | 16     | 24         | 18      | 10        | 7          | 13     | 5     | 244   |
| 1870–1880 | 29         | 7     | 14           | 51      | 47          | 13   | 7          | 21         | 38          | 61        | 31     | 57         | 47      | 27        | 24         | 37     | 21    | 532   |
| 1880–1890 | 27         | 11    | 15           | 43      | 41          | 17   | 10         | 18         | 27          | 74        | 34     | 58         | 46      | 24        | 22         | 39     | 22    | 528   |
| 1890–1900 | 24         | 19    | 10           | 39      | 37          | 20   | 22         | 24         | 42          | 52        | 25     | 61         | 55      | 28        | 33         | 29     | 29    | 549   |
| 1900–1910 | 22         | 13    | 11           | 33      | 32          | 8    | 17         | 26         | 42          | 53        | 23     | 66         | 57      | 31        | 25         | 20     | 19    | 498   |
| 1910–1920 | 19         | 7     | 18           | 36      | 23          | 14   | 13         | 33         | 51          | 30        | 26     | 53         | 45      | 28        | 21         | 24     | 16    | 457   |
| 1920–1930 | 27         | 8     | 8            | 30      | 27          | 11   | 18         | 43         | 58          | 36        | 17     | 42         | 37      | 20        | 14         | 16     | 13    | 425   |
| 1930–1940 | 23         | 18    | 21           | 64      | 43          | 14   | 29         | 28         | 74          | 46        | 32     | 49         | 58      | 41        | 33         | 33     | 22    | 628   |
| 1940–1950 | 18         | 9     | 7            | 25      | 30          | 9    | 27         | 20         | 37          | 22        | 9      | 26         | 29      | 18        | 18         | 12     | 16    | 332   |
| 1950–1960 | 18         | 7     | 9            | 38      | 34          | 12   | 24         | 42         | 46          | 25        | 13     | 37         | 40      | 33        | 27         | 19     | 29    | 453   |
| 1960–1970 | 33         | 10    | 6            | 26      | 44          | 19   | 20         | 41         | 54          | 8         | 16     | 23         | 23      | 17        | 22         | 19     | 12    | 393   |
| 1970–1980 | 12         | 3     | 6            | 11      | 11          | 3    | 7          | 19         | 26          | 13        | 10     | 27         | 23      | 25        | 8          | 15     | 5     | 224   |
| 1980–1990 | 16         | 2     | 4            | 13      | 15          | 5    | 10         | 18         | 34          | 6         | 22     | 24         | 29      | 21        | 11         | 8      | 16    | 254   |
| 1990–2000 | 23         | 2     | 14           | 25      | 22          | 7    | 19         | 29         | 45          | 9         | 36     | 50         | 55      | 28        | 20         | 26     | 23    | 433   |
| 2000–2010 | 42         | 12    | 21           | 45      | 46          | 19   | 10         | 34         | 55          | 35        | 30     | 43         | 45      | 26        | 11         | 28     | 11    | 513   |
| 2010–2020 | 8          | 3     | 9            | 30      | 31          | 5    | 3          | 2          | 23          | 19        | 23     | 33         | 44      | 25        | 13         | 23     | 18    | 312   |
| Total   | 429        | 146   | 202          | 654     | 622         | 247  | 295        | 462        | 751         | 612       | 434    | 767        | 732     | 467       | 368        | 433    | 320   | 7941  |
to the much greater area to be covered. Some additional information was found in individual national newspaper online archives including The Times, The Guardian, Daily Mail and Daily Mirror. Descriptive accounts of floods (as well as short period rainfall) in British Rainfall to 1970 and the Climatological Observer Link (COL) from 1970 were the most widely used sources. Additional information for the most extreme events was found in published books and papers, notably Eden (2008) with respect to weather disasters and Webb and Elsom (2016) for extreme hail events. The flood information for this recent period is still incomplete (compared with the period before 1950) and the chronology therefore requires a facility to enter additional information as it becomes available.

3.2 Surface water flash floods

The existing flood chronology for Britain, the Chronology of British Hydrological Events (CBHE) (Black & Law, 2004), is focused on river flooding although it does contain some reference to pluvial or surface water flooding. For river flooding, flood risk assessment depends heavily on long-term measured records of river flows and floods held by the NRFA and on historical information held by the Environment Agency (who are responsible for managing such risks) on the location and severity of floods. There are no such numerical or descriptive historical accounts of surface water flash flooding on which to base flood risk assessments in spite of the fact that it is a risk affecting approximately 3.2 million properties in England (Department of Environment, Food and Rural Affairs, 2018) (and presumably additional large numbers in Scotland and Wales). It was only in 2016 that surface water flooding was included in the national risk register in its own right for the first time (HM Government, 2017).

Currently the risk of surface water flooding is based on flood maps using a national model with detailed local topography. The map (Environment Agency, 2019) is based on rainfall intensity of a given duration (1, 3 and 6 h) and probabilities of occurrence (1:30, 1:100 and 1:1000) with hyetographs constructed on the basis of the Flood Estimation Handbook (FEH) 50% summer rainfall profile. The results show predicted patterns of flood extent, flow paths, depth and velocity based on modelled rainfall. However, the National Flood Resilience Review (HM Government, 2016) notes that areas at risk of surface water flooding can be much more difficult to predict than river or sea flooding and urges caution in its use since ‘surface water flooding is particularly sensitive to obstacles and small changes in ground level’. Greater uncertainty is likely to arise from inevitable assumptions in the modelling of ‘losses’ in the urban rainfall runoff process, including a fixed assumption of a rainfall reduction of 12 mm/h to represent the effects of a typical sewer capacity. In addition the conveyance effect of ordinary watercourses or drainage channels is not explicitly modelled and structures (such as bridges, culverts and weirs) are not represented.

There is clearly a need to supplement or even validate this modelled data with observed event information. Some local information supplied from local authorities has been incorporated into the model but detailed local information is only available since the Flood and Water Management Act 2010 (Section 19) which placed a statutory requirement on local authorities to undertake investigations of significant flooding events, including those from surface water and ordinary (smaller) watercourses. Section 19 reports are now widely available on the internet for recent events. Such reports include the possibility of adding comparative information from events before 2010 but most such reports are sparse or absent. (Details from Section 19 Reports have not yet been added to the chronology.) Before the 2010 Act there was no responsibility to retain such flood records.

Severe surface water floods occur infrequently at any one location so that there may be no relevant observations to compare with the magnitude of a recent event. However, extreme surface water flooding events occur somewhere in the United Kingdom multiple times within a decade. There is therefore a need for a unified national source of historical information which can be drawn upon to assess the detailed historic impact and frequency of surface water flood events for specific locations. This national chronology of flash floods provides the first basis for such assessment.

Both the early and the extended chronology have compiled descriptions, primarily from newspaper sources, of the effects of intense rainfall in urban areas. Information relevant to assessing severity has been extracted to enable comparisons to be made of sources, flood pathways, areas and extent of repeated ponding. Depths in streets and named buildings, such as churches, hotels and public houses are included. Flow velocities are absent though some indication may be made through effects on individuals washed off their feet.

There are obvious limitations in using historical flash flood data in urban areas and comparing this with recent floods. Changes in the urban surface permeability (likely to increase flood risk) and improvements to sub-surface drainage (likely to decrease flood risk) can affect flood risk at particular locations (Archer et al., 2017). However, in extreme events, where the rainfall intensity is far in excess of the design capacity of both current and historical drainage systems, surcharging of sewers exceeding
3.3  |  River flash floods and walls of water

Conventional flood risk assessment is primarily concerned with the probability of peak flood water levels and its impact on costs and damage to property. However, the extent to which householders can take remedial action to remove property to safe levels depends on the rate at which the water rises. Damage is therefore also related to rate of rise in level, but rapidly rising levels have a much more serious effect on risk to life (Archer & Fowler, 2014; Few, Kovats, Matthies, & Ahern, 2004). Unexpected rates of rise in water level can trap householders in places from which they cannot escape, for example in bungalows or caravans. Even when peak levels achieved are not great, rapid rates of rise in water level pose a threat to fishermen and recreational users. Archer and Fowler (2014, 2018) note many historical examples of deaths arising from extreme rates of rise and especially when associated with severe peak flows such as at Lynmouth in 1952 (Dobbie & Wolf, 1953). Hazards from rapid rate of rise in river level are rarely considered in flood risk assessments.

The most critical incidents are where the rate of rise is near instantaneous, appearing as a visible wave and described 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. The description as a wave is substantiated in each case by the associated impacts on river users and property. A trawl through the chronology identified 289 events described in this way, or approximately once a year over the last 300 years somewhere in Britain. This number is likely to be a serious underestimate of occurrences as many such events will go unobserved, for example in remote locations or occurring during darkness. Even if observed they may not be reported if they have not caused any serious incidents.

Walls of water are most commonly observed in upland areas of Wales, Scotland and northern England (Table 2) where nearly all major rivers draining the Pennines have reported multiple incidents both in headwaters and in populated areas along main rivers, with many accounts of deaths. Archer and Fowler (2018) note that flash floods originating in upland tributaries may be transmitted downstream with a steepening wave front over tens of kilometres. In addition, they note that such severe flash floods are generated by intense rainfall alone and do not require the occurrence of a blockage and release in the upstream catchment. Rapid rates of rise are uncommon in the south and east of England and confined to headwater tributaries but there are extreme cases where dry or intermittent rivers are reactivated and cause death and disruption, for example in the River Lud at Louth in Lincolnshire in 1920 (Clark and Arellano, 2004).

Decadal totals of ‘walls of water’ events (Table 2) indicate greater numbers of events from the mid-nineteenth to the mid-20th century. Declining observations in recent decades are unlikely to reflect a real decrease and are thought to be caused by the dearth of local newspapers in the BNA (less than 10 in recent decades compared with several hundred in the late 19th century). Two regions, Southwest and Northeast, where there was a more intensive search of local newspapers for the early archive show continuing comparable frequency in this later period. Similar low numbers before 1840 are also a reflection of the small number of local newspapers available although the most extreme events are likely to be recorded.

3.4  |  Intense rainfall

The purpose of the SINATRA project, for which the early chronology was prepared, was to investigate ‘flooding from intense rainfall’ and intense short-duration rainfall has been the cause of the flash flood incidents described in the chronology. Flash floods resulting from failure of dams or embankments have been omitted, except where the rainfall has caused flooding on its own account. However, through most of the historical record, measurements of rainfall intensity have been absent or limited to a few point measurements, so the severity of rainfall causing the flood must be assumed on the basis of the ensuing damage.

In addition, available records of rainfall intensity are limited in their ability to define the severity and extent of intense convective rainfall. From the latter half of the 19th century rainfall observers have used their daily rain gauges to assess rainfall intensity by noting the time of the beginning and end of an intense rainfall event and the accumulated amount, and these records were the basis for entries (along with the recording rainfall records noted below) in British Rainfall (1870–1968) under the heading of ‘Heavy falls in short periods’. The reliability of these records depends upon the accuracy of timing and the diligence of the observer. However, these records have been extracted to the chronology for events with durations usually between 15 min and 2 h.

Over the past 50 years there has been a rapid increase in the number and reliability of recording gauges but a
| Decade       | Northumbria | Swale | Moors | N York | Eden | Lakes | South | Southwest | Scotland | Trent | Southeast | Southwest1 | Severn | Wales | Total |
|-------------|-------------|-------|-------|--------|------|-------|-------|-----------|----------|-------|-----------|------------|--------|-------|-------|
| <1700       | 1           | 1     | 1     |        |      |       |       |           |          |       |           |            |        |       | 2     |
| 1700–1750   | 2           | 1     | 1     |        |      |       |       |           |          |       |           |            |        |       | 5     |
| 1750–1800   | 1           | 1     |       |        |      |       |       |           |          |       |           |            |        |       | 4     |
| 1800–1850   | 1           | 1     | 1     |        |      |       |       |           |          |       |           |            |        |       | 4     |
| 1850–1900   | 1           | 1     | 1     |        |      |       |       |           |          |       |           |            |        |       | 4     |
| 1900–1950   | 2           | 1     |       |        |      |       |       |           |          |       |           |            |        |       | 4     |
| 1950–2000   | 1           | 1     | 1     |        |      |       |       |           |          |       |           |            |        |       | 4     |
| 2000–2010   | 1           | 1     | 1     |        |      |       |       |           |          |       |           |            |        |       | 4     |
| 2010–2020   | 1           | 1     | 2     |        |      |       |       |           |          |       |           |            |        |       | 4     |
| Total       | 38          | 6     | 7     | 31     | 30   | 20    | 24    | 40        | 26       | 5     | 6         | 4          | 6      | 9     | 269   |

The table represents the decadal number of ‘walls of water’ events in each region from different dates, excluding the ‘Early chronology’ and ‘Extended chronology’ columns.
gauge catch area individually represents less than 0.00001% of 1 km² and there are only approximately 1900 recording gauges in Britain or 1 per 130 km² (Lewis et al., 2018). Equally, information on extreme short-duration rainfall from gauge records is also relatively short, restricted to the last few decades (Blenkinsop, Lewis, Chan, & Fowler, 2017). Given the spatial variability of intensity in convective rainfall, it is very unlikely that any raingauge will have measured the maximum intensity within the storm. Archer and Wheeler (1991) give an example of a storm with rainfall amounts measured by four gauges at 2 min intervals within an area of 1.5 km² where hourly rainfall totals varied from 27 to 40 mm and assessed return period varied from 30 years to 180 years. Some storms are missed entirely by ground based raingauges and there are thus many events with severe flooding where there are no rainfall records. An analysis of data from Germany and the United Kingdom suggests that the sparse gauge network is only able to capture around 20% of intense short-duration (hourly) rainfall events seen in the radar record (Lengfeld et al., 2020). Blended, gridded datasets such as the UKGrshHP high-resolution radar-gauge-satellite product (1 km, 1 h resolution: Yu, Li, Lewis, Blenkinsop, & Fowler, 2020), with complete spatial coverage, have the potential to provide improved information on the frequency of short-duration intense storms that trigger surface water flash flooding, but since the radar and satellite records are short, only start in the early 2000s.

Conversely, there are many events where intense rainfall has been recorded but without reported consequential flooding. This may be simply because no floods have occurred, for example with dry ground or permeable soils able to accept the incident rainfall. Kaiser et al. (2020) recommend that such ‘negative’ events where heavy precipitation did not cause a flash flood, be included in a database to help understand threshold conditions for flooding. However, the majority of cases with intense rainfall but no reported flooding are because flood information sources have not yet been identified. For example, intense rainfall reports by the Climatological Observers Link (1970–2019) focus on the meteorological aspects of the event and rarely give detailed information on the resulting flood, especially for surface water floods. Thus it is necessary to provide a facility for users to update the chronology when flood details are identified to match the existing rainfall record.

3.5 | Hail

Hail has a contributing role in flooding and significant events have been extracted from historical sources and included in the chronology. The effect is mainly felt with respect to flash floods caused by surface runoff rather than from the overflow of rivers (Archer, 2016). There are three principal effects by which hail can enhance the impact of flooding:

- **Access through broken windows**: There are numerous historical accounts of flood damage caused by large hail. Very large hail or ragged pieces of ice, especially accompanied by strong winds has broken windows, skylights and even roof tiles and allowed the access of hail and accompanying rain (and shattered glass) into buildings. The chronology has many accounts of towns and villages with windows on every house broken in the direction facing the wind. Observers give accounts of measurements of hail by weight (100 g or more) or by dimensions (by diameter where spherical – or by length and width where irregular) or simply by comparison with walnuts (21–30 mm diameter), pigeon’s (31–40 mm) or pullet’s eggs (41–50 mm) (Torro Size scale) (Webb, Elsom, & Meaden, 2009). Heymsfield, Giammanco, and Robert Wright (2014) developed size-dependent relationships for terminal velocities and kinetic energy of large hail. Typically the terminal velocity of a 5-cm diameter hailstone is 31 m/s, with a kinetic energy of 24 joules (or >800 J/m²). A hailstorm in London in 1846 caused flood and window breakage to the Houses of Parliament and Buckingham Palace. In the storm at north Yorkshire and neighbouring Cumbria in 1893, hailstones as large as hen’s eggs were reported and hundreds of thousands of panes of glass broken, people injured and poultry killed, and streets and house interiors flooded (Archer, 2016). Breakage of windows has much diminished with improvements in glass strength, initially with the French invention of drawn glass in 1904, but only used widely in England after 1920, and then with the creation of float glass in 1959 which remains the basis for modern windows (Dungworth, 2011).

- **Blocking of roof gutters**: A sufficiently heavy fall of hail, especially when mixed with rain, can accumulate in roof gutters causing water to overflow. Blockage of gutters can cause the rain to run directly down the front of buildings, to gain access to interiors and add to surface water rather than being evacuated by the drains.

- **Coalescing and blocking of drains**: Intense hail may accumulate in drifts several feet in depth, usually with hail of small rather than large diameter. Hail may coalesce and block road drains so that melted hail and accompanying rain cannot drain away, causing serious flooding of land and property. The most severe recent event was at Ottery St Mary, Devon on October 30, 2008, an unusually late date in the year. Drifts of hail were up to car roofs and in one case a fire crew became embedded in a 2-m drift. People were rescued from homes, flooded
to a depth of 1.2 m, with some being airlifted to safety. Precipitation, mainly of hail, was estimated at 160 mm in a 3-h period (www.metoffice.gov.uk/learning/learn-about-the-weather/weather-phenomena/case-studies/ottery-hail). The event is not unique; a similar event occurred in Camelford in Cornwall in June 1957 when 140 mm of rain and hail fell in 3 h. Bleasdale (1957) describes how masses of hailstones, some of them congealed into large blocks, were washed about by the flood waters. Hailstones were ‘as big as ping pong balls’. The hailstones formed themselves into ice floes, choking drains and building up reservoirs for the flood water. Houses, shops, cafes were flooded to 2–3 ft (0.6–0.9 m) and four bridges over the River Camel were either destroyed or damaged. Events are not restricted to the Southwest; the village of Wold Newton in the East Riding of Yorkshire was hit by a storm on August 12, 1938 with 2 ft of accumulated hail from which cars had to be dug out and water a foot deep rushed through the village. In Lancashire on July 11, 1964 widespread flooding with the most intense precipitation reported at Bolton with 55.9 mm in 15 min. In Warrington hailstones piled up 2 ft deep in some streets and cars and a tanker had to be extricated.

Events where large hail or deep accumulations of hail have occurred, even with no accompanying reports of flooding, are included in the chronology as a supplement to the TORRO hailstorms index (http://www.torro.org.uk/hail_info.php).

4 | DISCUSSION

The chronology presents a comprehensive historical account of flash floods as defined by the rapidity of onset (threat response time and rate of rise in level), which is a distinct hazard from the impact of the peak flood level. Risks from rapidly rising water levels are more serious than peak level with respect to human life; the chronology provides many examples of deaths by drowning of individuals in these circumstances.

The principal source for the chronology is the BNA but the sharp reduction in the number of newspapers archived after 1960 has undoubtedly influenced the number of flash floods identified in recent decades. Whilst the most extreme events in this period are still likely to have been reported in national papers and other sources, the absence of comprehensive cover and the loss of smaller events during this later period restrict the validity of time series comparisons. There is therefore a need to ensure there are facilities for updating the chronology from local sources where possible.

The chronology for the first time provides a record of surface water floods and their impact on cities, towns and villages. Flood risks from surface water are currently provided by flood risk maps for surface water in England (Environment Agency, 2019). These maps were created using data from local authorities and modelling of potential flow paths and ponds taking account of local topography using a 2 m square grid and rainfall of different severities and storm durations. Past flooding information has also been used but is limited in the duration of its cover. The chronology provides an additional source for surface water flood risk assessment to the mapped risk based on modelling and may provide a better basis for risk assessment for the most extreme events, which are unlikely to have occurred in the recent past.

The chronology draws attention to the prevalence of very rapid rates of rise in river level either as ‘walls of water’, or at a rate which has caused deaths by drowning, or at a rate likely to endanger life. Whilst the phenomenon is not common, the total catalogued walls of water of nearly 300 over the period from the early 18th century, suggests that far more consideration should be given to the threat than is currently the case. This is particularly the case with global warming as the short-duration intense rainfall events that trigger such rapid rates of rise are projected to significantly increase in frequency (Kendon et al., 2014). Incidences in the chronology suggest that walls of water are much more common in upland areas of Northern England, Wales and Scotland than in lowland rivers in south and east England. However, the records are likely to seriously underestimate the frequency of occurrence in remote upland catchments, where events have occurred at night or where the event has not caused an observed threat sufficient to receive journalistic comment. Even the event described on the river Tyne and reported in Archer and Fowler (2018), of a rise in level of more than 1.2 m and a rise in discharge of more than 150 m³/s between 15 min observations was not reported in newspapers. The standard measurement interval for river level of 15 min does not capture the properties of these translatory wave fronts. Consideration should therefore be given to measurement at a shorter time interval on selected ‘rapid response’ catchments.

In 2006 the Environment Agency developed a register of ‘Rapid Response catchments’ using three criteria, the speed of response based on the time to peak of the UH, the severity of flooding and the presence of vulnerable populations (Francis, 2010). Whilst the principal criterion used here for flash floods is also the speed of response, rapid rise in water level for example in ‘walls of water’ are a hazard even when the peak flood level is not severe and they may occur where there is no obvious vulnerable population. There is a need to review the definition of rapid response catchments in terms of risk of the
infrequent occurrence of extreme rates of rise on catchments with a usually normal response. This chronology offers the opportunity to define such catchments on the basis of observed locations of historic occurrences.

Observations in the chronology raise many practical and theoretical issues with respect to flood risk assessment and warning. What are the catchment and river channel characteristics on which the risk from rapid rate of rise is greatest? How are the waves generated? How far downstream can such a wave persist? Is the much reduced catchment lag between rainfall and runoff peak with increasing rainfall intensity as illustrated by Wass et al. (2008) the result of reduced time in the land phase or the channel phase (or both) of catchment response? Does ‘walls of water’ wave travel velocity differ from normal waves in the same channel? With respect to response, is it possible to forecast the occurrence of rapid rates of rise from observed or forecast rainfall? What is the threshold of rainfall intensity where the catchment response changes from a normal attenuating hydrograph to a translatory wave? How should forecasting systems be set up to warn river users of the approach of such a threatening wave?

From a practical point of view, the occurrence of very rapid rate of rise in rivers where the normal response is more prolonged, calls into question the viability of the UH method of determining a design flood hydrograph. This is still widely used in Britain and elsewhere because of its simplicity. Weaknesses in the UH method have been widely demonstrated (Shaw, 1994) but only recently with respect to the assumption that the effective rainfall runoff relationship does not change with time, whatever the unit of rainfall is applied. The influence of shorter time to peak for more intense rainfall has been recognised by Faulkner and Barber (2009) who note that use of the UH method in such situations could result in underestimation of peak flows (and unreliable hydrograph shape) and recommend further research to investigate whether there are characteristic catchment or event types for which this effect occurs. The chronology demonstrates the widespread but infrequent occurrence of such rapid rates of rise and provides the opportunity to define catchment susceptibility and rainfall event types that trigger such translatory waves.

Table 1 demonstrates that flash flood occurrence varies by decade and that even greater variation is seen on an annual basis. Whilst there are some limitations with respect to recent data, the chronology therefore has the potential for assessing trends and variability, as illustrated by Archer et al. (2017) for northeast and southwest England using the early chronology. It also provides an opportunity to determine links between flash flood occurrence and broad-scale circulation systems such as the North Atlantic Oscillation, which affect weather patterns across the United Kingdom. Understanding the drivers of flash flooding is important since the intensity of rainfall has been observed to increase with global warming (Westra, Alexander, & Zwiers, 2013), with short-duration intensities increasing in most parts of the world (Fowler et al., 2021). This is consistent with and is projected to increases in rainfall intensity from climate models (Fischer & Knutti, 2016; Kendon et al., 2014), with flash floods likely to increase in frequency or severity. The chronology provides important information on flood risk which augments our understanding of current climate variability; a standard with which future changes can then be compared.

5 | CONCLUSIONS

1. The chronology provides a record of flash floods in Britain based on data collated mainly between 1700 and 2020.
2. Flash floods are defined in terms of rapidity of onset – a separate hazard from flood peak level.
3. The chronology provides the first historical records of surface water flooding which can be used to supplement current flood risk assessment based on modelling.
4. Rapid rates of rise in rivers as ‘walls of water’ or sufficient to endanger life by drowning are highlighted with nearly 300 such events identified.
5. Such rapid rates of rise raise practical and theoretical issues with respect to flood risk assessment and warning.
6. Precipitation as hail can have a serious confounding effect with rainfall on flood occurrence.
7. Variability from year to year provides an opportunity to investigate links to broad scale weather patterns which will be important in understanding the drivers of flash flood events, from a forecasting and climate adaptation perspective.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are openly available in a JBATrust website at https://www.jbatrust.org/how-we-help/publications-resources/rivers-and-coasts/uk-chronology-of-flash-floods-1

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