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The winter 2015/2016 floods in the UK: a hydrological appraisal

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Introduction

The flooding in winter 2015/2016 was one of the most extraordinary hydrological episodes witnessed in the UK in recent decades. The winter was defined by a succession of severe storms, bringing extreme rainfall and associated widespread flooding across northern and western regions. For the UK, December 2015 was the wettest month (for any calendar month) and it was the second wettest winter (December–February) in a series from 1910, while a number of new records were established for rainfall accumulations over shorter timescales (McCarthy *et al.*, 2016; Burt, 2016). The hydrological response was remarkable; period of record maximum peak flows were established across northern areas of the UK, and the high flow response was notable in terms of its spatial extent, duration and frequency. The flooding had severe impacts on properties, infrastructure and livelihoods. Inevitably, the flooding was at the forefront of public, political and media attention through much of the winter and, occurring only two years after the major flooding of 2013/2014, led to a significant debate around flood management in a warming world.

This paper describes the hydrological characteristics and widespread impacts of the winter 2015/2016 floods, places the event in historical context and briefly considers the wider narratives surrounding the events. Companion papers in this issue describe the meteorological events (McCarthy *et al.*, 2016) and the meteorological records broken (Burt, 2016). Together, it is hoped that these papers provide a comprehensive overview of the exceptional meteorological and hydrological conditions and their impacts in the winter of 2015/2016. The term 'winter floods' has been widely adopted, and reasonably so given the focus in the winter months of December and January. We use that terminology here, although the hydrological conditions before and after the meteorological winter (December–February) are important for the wider context so are considered in this paper where appropriate.

Data and information used in this paper are primarily sourced from the National Hydrological Monitoring Programme (NHMP). Supplementary data and information was provided by the UK Measuring Authorities. The NHMP collates data for 104 index river gauging stations and 37 index groundwater boreholes in the UK alongside rainfall, soil moisture and reservoir data to produce the monthly Hydrological Summary (http://nrfa.ceh.ac.uk/monthly-hydrological-summary-uk). Data submitted to the NHMP by the UK Measuring Authorities are provisional, and any records reported in this paper may be subject to change. The total outflows for Great Britain mentioned in this paper are routinely used by the NHMP to identify national scale runoff trends and to make comparisons between extreme events. Details of their calculation method are outlined in Marsh *et al.* (2015). Figure 1 shows the location of selected catchments referred to throughout this paper.

Chronology of the flooding

Through the first half of 2015, river flows in the UK were generally rather unremarkable and remained within the normal range in the majority of catchments. The early autumn was very dry in northern and western parts of the UK. Consequently, contrary to the typical seasonal response, October saw steep recessions in some northern and western catchments; in northwest Scotland, the Carron and Naver recorded new seasonal daily flow minima.

The drier conditions continued into early November, and estimated outflows from Great Britain were less than half of the average for the time of the year. Thereafter, the month was dominated by mild and unsettled weather, including a sequence of Atlantic low pressure systems. Following

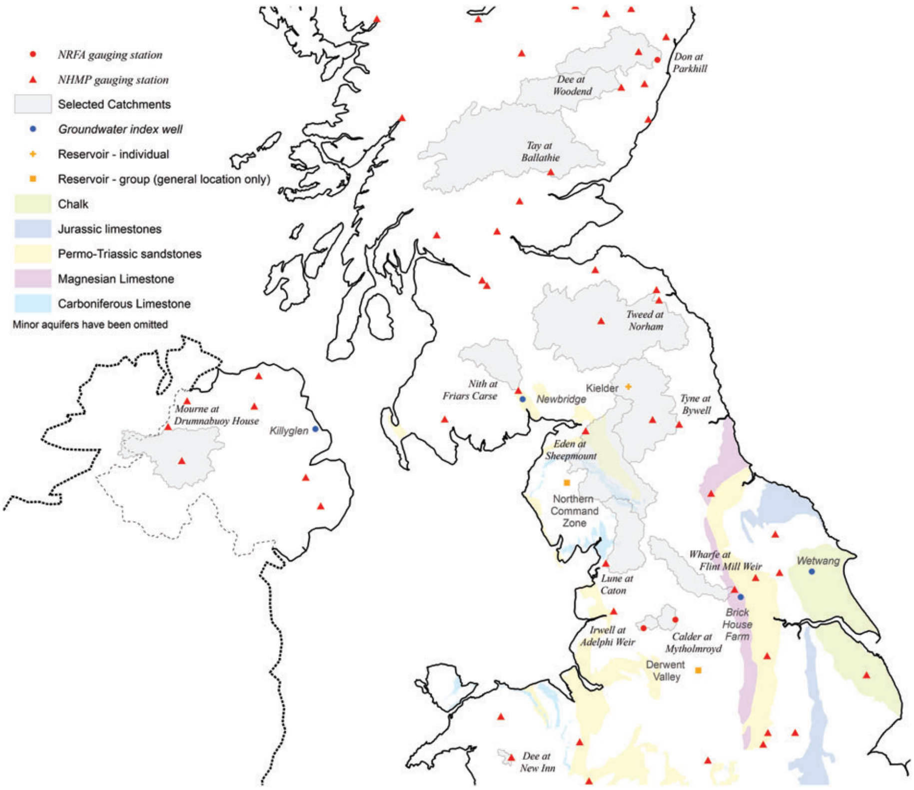

Figure 1. Location of gauging stations, boreholes and reservoirs referred to in this paper.

a Met Office/Met Éireann pilot initiative to name winter storms, November saw the first three named storms in the British Isles (Storms *Abigail*, *Barney* and *Clodagh*; McCarthy *et al*., 2016). The associated rainfall prompted a dramatic hydrological transformation, and many of the catchments that recorded below average flows in October recorded notably high flows in November. By mid-month, Flood Warnings were widespread across much of northern Britain – severe warnings were issued in Kendal and Egremont on the 14th/15th, prompting property evacuations. A number of major rivers draining the Pennines registered new November peak flow records (e.g. the Ribble, Lune and Wharfe). Average flows for November were exceptionally high in a band from north Wales to the Scottish borders, exceeding twice the average, and the Wharfe recorded its highest November

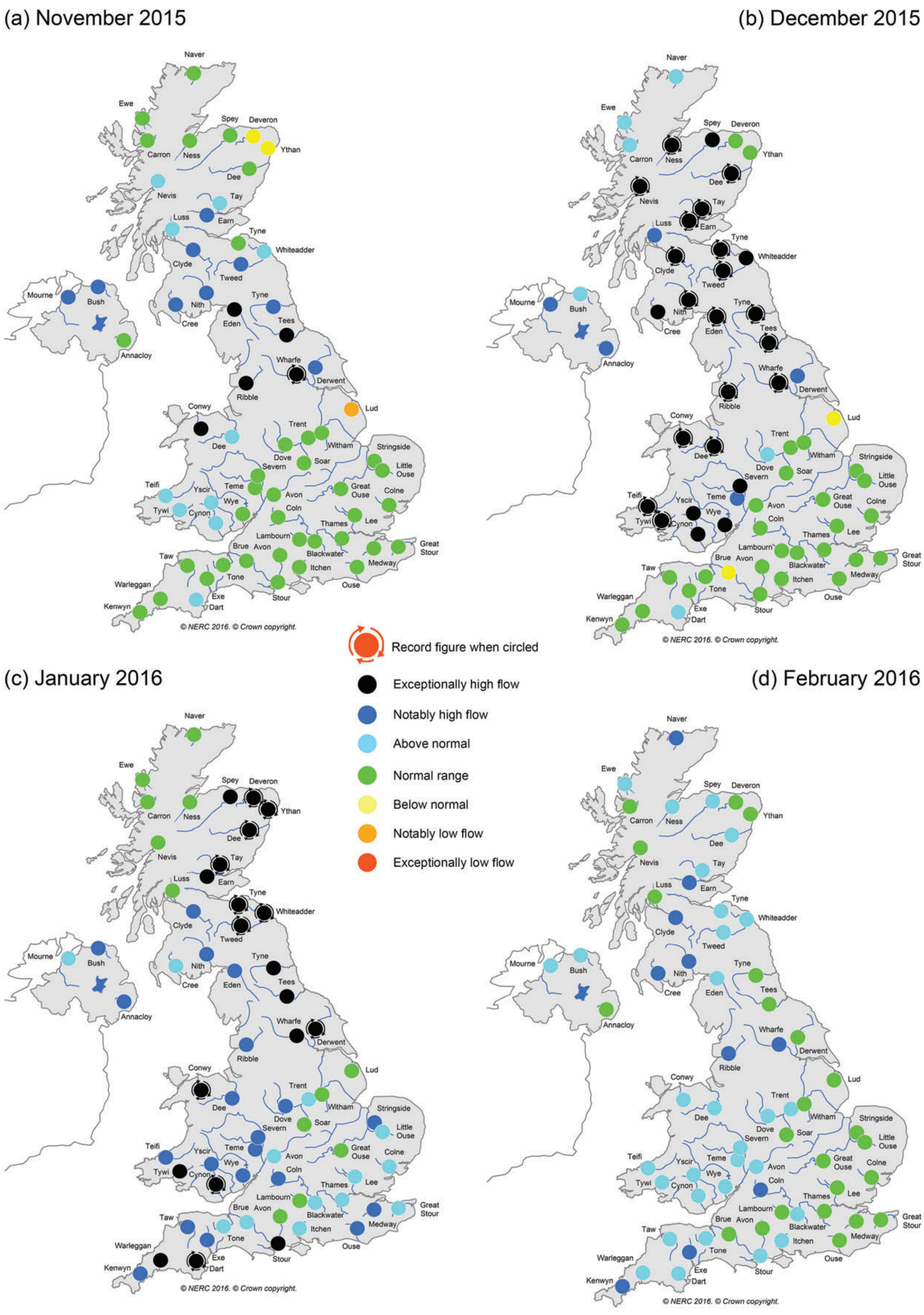

Figure 2. Monthly mean river flows for November, December, January and February. New period of record maxima are circled with arrows.

runoff in a series from 1955 (Figure 2(a)). Outside this area, flows were notably high across southern Scotland and Northern Ireland, while flows in the rest of UK were average or below.

Following the wet November, soils in many northern and western catchments were saturated (as is typical for the time of year), and river flows were already increasing entering December (Figure 3). The stormy weather continued, and on 5th/6th December, Storm *Desmond* brought heavy and persistent rainfall across much of Ireland, northwest England and southern Scotland. New maximum 24h (341mm at Honister Pass) and 48h (405 mm at Thirlmere) rainfall records were established in Cumbria (McCarthy *et al*., 2016; Burt, 2016), and new peak flow maxima were registered in many catchments across northern regions of the UK as a devastating flooding episode unfolded (the impacts of which are discussed in a later section). Due to the exceptional rainfall and river flows associated with Storm *Desmond*, large volumes of sediment and debris were transported in watercourses and deposited when flows began to recede, drastically reducing channel conveyance. This contributed to several communities in the Lake District (e.g. Glenridding) being flooded three times before Christmas, when further intense rainfall events affected northern England.

While the passage of Storm *Eva* on 23rd/24th December brought strong winds but only modest rainfall, a slow-moving low pressure system brought further exceptional rainfall totals on the 25th/26th, and 100–120mm fell over the southern Pennines (McCarthy *et al*., 2016). By Boxing Day, the number of Flood Warnings across Wales and northern England totalled 500 (including the severe warning, warning and alert categories), with widespread warnings across Scotland. A large swathe of northern Britain recorded exceptional river flows and floodplain inundations were witnessed in many locations. Following the record peak flows in November, several rivers draining the Pennines recorded new peak flow maxima on the 25th/26th (e.g. the Nidd, Wharfe, Aire, Calder and Irwell). With more rainfall falling on already saturated ground between Christmas and New Year, high flows persisted. The arrival of Storm *Frank* on 29th/30th December saw flows on the Scottish Dee exceed their previous maxima (in a series from 1929; Figure 3(b)) by a considerable margin, and a new maximum peak flow was recorded on the Cree (in a series from 1963). Due to the persistent and exceptional rainfall during December, monthly mean river flows established new records for any month in the majority of catchments in a band from southwest Wales to northeast Scotland (Figure 2(b)). Of these catchments, the Tyne, Tees, Wharfe, Conwy and Eden recorded more than three times the December average (in record lengths of more than 45 years).

Entering 2016, soils remained saturated and river flows remained exceptionally high across much of northern and western Britain. With many catchments vulnerable to even moderate rainfall, river flow records were once again established in January as the UK recorded its fourth wettest January on record (in a series from 1910). From the 4th to the 7th, new January peak flow records

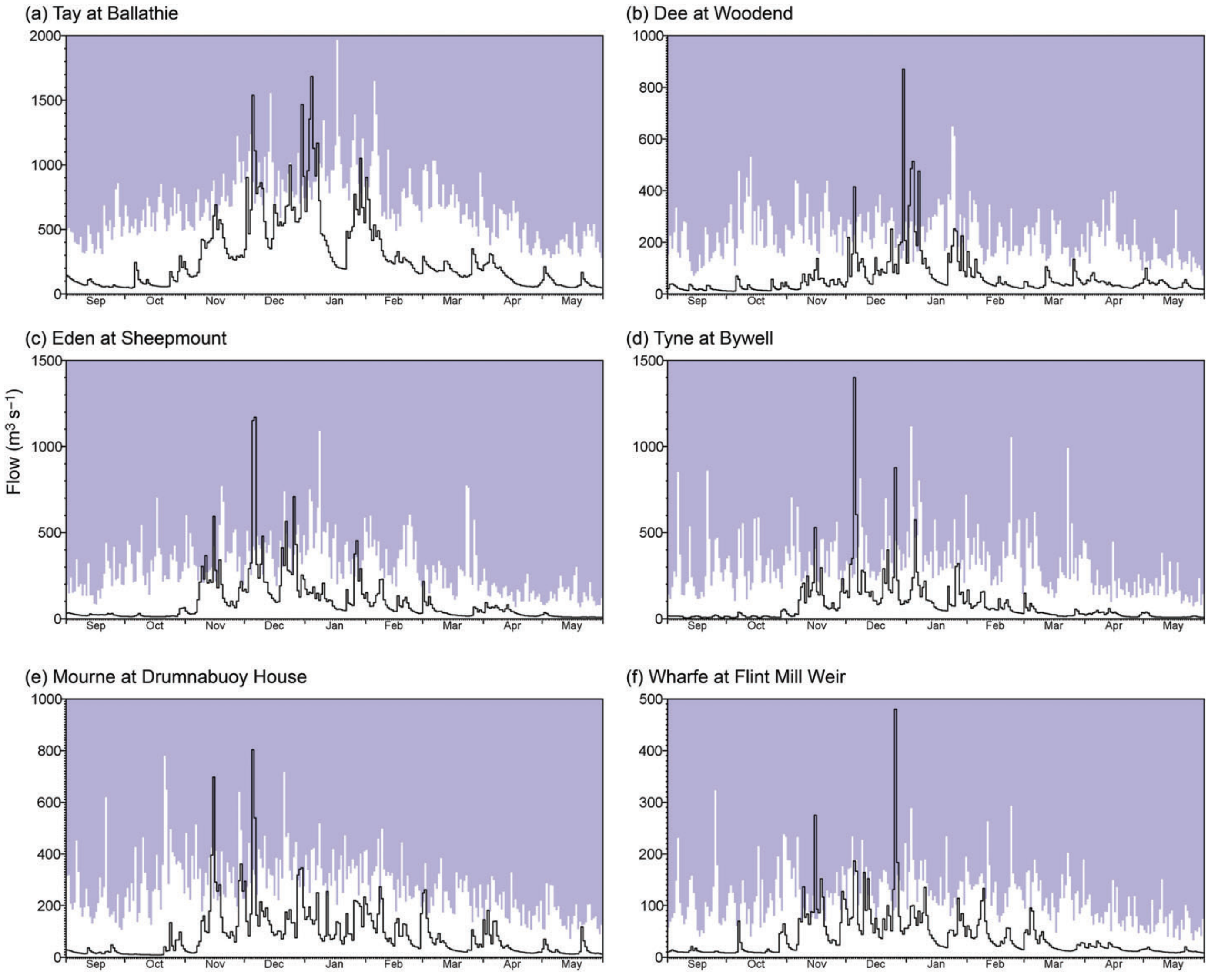

Figure 3. Daily river flows (m^3s^{-1}) for the period September 2015 to May 2016. The blue envelope shows the highest daily flows on record.

Table 1

Ranked Great Britain outflows (m^3s^{-1}) averaged over a range of n-day periods (in records since 1961).

5 days		*10 days*		*30 days*		*90 days*	
7 Dec 2015	22 169	8 Feb 1990	19 905	14 Jan 2016	16 449	11 Feb 2016	13 593
8 Feb 1990	22 053	8 Jan 2016	19 789	21 Feb 1990	15 938	12 Mar 2014	12 949
11 Jan 2005	21 542	14 Dec 2000	18 931	19 Jan 2014	15 029	16 Mar 1990	11 456
7 Jan 2016	20 798	31 Dec 2012	18 828	18 Dec 2006	14 552	6 Jan 2001	11 383
24 Dec 2012	20 508	10 Dec 2015	18 435	24 Feb 2014	14 468	6 Mar 1995	11 142

The date shown is the end date of the n-day period. Flows during the period November 2015–January 2016 are highlighted in grey.

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were registered in catchments across northeast Scotland. The Deveron recorded a new January maximum (in a series from 1960), the Don a new maximum for any month (in a series from 1971), and the Ythan a new maximum for any month by a wide margin (in a series from 1983). Furthermore, new daily maximum flows were established on the Ythan and Don for 12 consecutive days, illustrating that both the individual events and duration of high flows were exceptional. With more settled conditions mid-month, recessions became established, and flows on some rivers fell below average for the first time since early November. However, these were interrupted towards month-end as river flows rose again in response to frontal systems, including Storm *Gertrude* on 28th/29th January. Over 100 Flood Alerts and Warnings were issued in northern and western catchments, but peak flows were not as remarkable as those recorded in the previous month. January was also very wet in parts of central and southern England, particularly the far south – places that had seen more typical winter rainfall. Some seasonally high flows were recorded in Wales and southern England, including the second highest flow on record on the Lymington (in a record from 1976). New record monthly mean flows for January were recorded in catchments across eastern Scotland (e.g. the Scottish Dee recorded more than three times the average in a series from 1929) and in parts of Wales (Figure 2(c)), some of which also set new records in December.

February was the driest of the winter months, but still registered above average rainfall in the majority of regions in the UK (McCarthy *et al.*, 2016). River flows were high entering the month as a result of the substantial late-January rainfall, and more peak flow records were established during the first week with the passage of Storms *Henry* and *Imogen*. On the 1st, Flood Alerts and Warnings were issued across Scotland following Storm *Henry*; the Naver registered a new February peak flow maximum (in a series from 1978). Over 100 Flood Alerts and Warnings were issued on the 6th, following further rainfall; flows rose sharply in rivers in Wales and southwest England, and the Tone registered a new February peak flow maximum (in a record from 1961). Warnings were issued again on the 8th/9th during the passage of Storm *Imogen*, and seasonally high flows were recorded on some rivers in central and southern England (e.g. the Trent, Blackwater and Dorset Stour). From mid-month, drier conditions prevailed across the UK, heralding steep recessions; by month-end some responsive catchments (many of which established several records over the winter) registered flows half of the average for the time of year. Despite the drier end to February, monthly mean flows were above average across most of northern and western Britain (Figure 2(d)), and more than 150% of average in a number of catchments.

Following the exceptional winter, the spring was dry in northern and western catchments, prompting a marked shift in river flow response. Although interrupted by some seasonally high flows, long and often steep recessions were observed on many rivers. By the end of May, flows on the Eden were notably low, with new seasonal daily flow minima recorded on 12 consecutive days and on 19 days in total, a stark contrast from a new maximum peak flow 5 months earlier following Storm *Desmond*.

Severity of the winter river flows

In this section, the exceptional nature of the river flows of winter 2015/2016 are characterised and quantified. The magnitude, duration and spatial extent of the November 2015–January 2016 runoff can first be illustrated at a broad scale by considering national outflows. On 5th December, daily outflows from Great Britain eclipsed the previous maximum daily outflow (14 December 2006) by more than 30%, following the exceptional rainfall of Storm *Desmond*. Similarly, outflows from Great Britain on 6th, 26th and 30th December ranked third, fifth and sixth, respectively, in a series from 1961. These exceptional outflow estimates are despite moderate flows across much of the south and east of England. The intense and prolonged nature of the winter flooding is reflected in the *n*-day average outflows from Great Britain (Table 1). Average flows across two separate 5-day periods in December and January feature in the top five, including the highest on record. Outflows for the 2015/2016 events were the largest on record for periods of 20 up to 90 days, exceeding those from recent notable events such as 2000, 2012 and 2013/2014 (Table 1).

Monthly mean flows for individual months from November to January highlight new maxima across much of northern and western Britain (Figure 2). These new monthly maxima translated into new records for November–January average flows in 37[1] catchments in a band extending from southwest Wales and Northern Ireland to Yorkshire and northeast Scotland (Figure 4), many of these approaching or exceeding 200% of their average flow. In many catchments across the north and west, the 3-month average flows exceeded previous maxima for any such period of record – by more than 30% on the Scottish Dee, Tweed, Tyne, Eden, Wharfe, Ribble and Conwy.

The severity of the flooding in winter 2015/2016 is most appropriately captured by the instantaneous peak flows (based on 15-minute resolution flow data) for individual catchments, and their associated return periods. Return periods were estimated using the improved Flood Estimation Handbook (FEH) statistical method (Kjeldsen et al., 2008). The NRFA Peak Flows v4.1 provided a source of candidate annual maximum records to which enhanced single-site analysis was applied using an automated procedure. This standard application did not allow for the use of additional local or historical flood information. Table 2 shows the peak flow magnitude and estimated return period range for selected large catchments across northern and western areas of the UK, illustrating the wide geographical spread of new maximum peak flows. Although this is just a selection, it was reported at the time by the Environment Agency that new river flow maxima were recorded across north-

[1]Note that this is based on 104 index catchments used in the NHMP. It is likely that more records were established across the wider gauged network.

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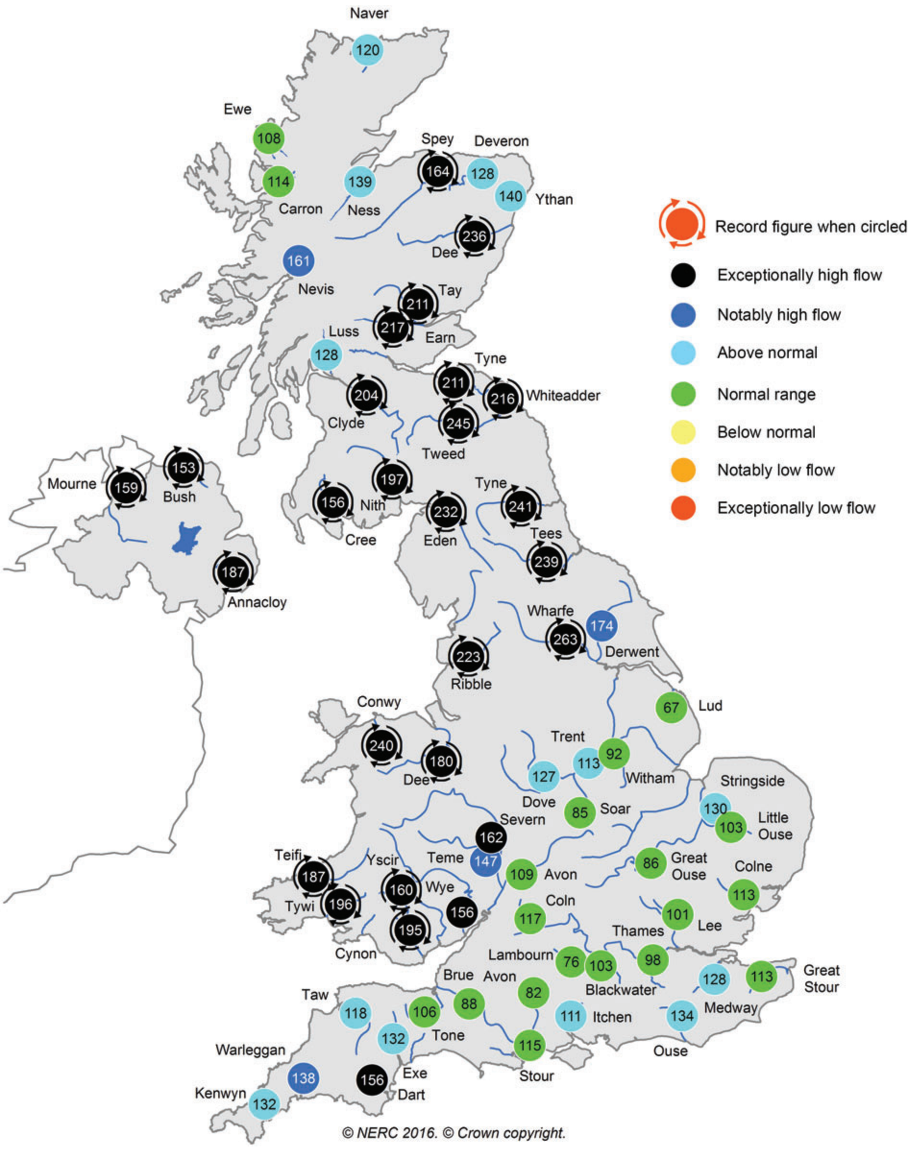

Figure 4. Mean river flows for November 2015 to January 2016 expressed as a percentage of long-term average flows. Note: new period of record maxima are circled with arrows.

ern England (Curtin, 2016); the full spatial extent of record-breaking flows will require assessment when quality controlled river flows become available.

New maximum peak flows in the instrumental era for England and Wales of ~1700m^{3}s^{-1} were established on 5th/6th December on the Eden and the Lune in northwest England, and the Tyne in northeast England, following Storm *Desmond*. Table 2 shows that the peak flow recorded on the Eden exceeded the previous maxima in January 2005 by 10%; both events were associated with severe flooding in Carlisle. The estimated return period for the peak flow on the Eden exceeds 200 years, whilst for the Lune and Tyne estimates are within the 100-200 year range. It is important to emphasise that these records are from gauged series that start in the 1950s/1960s, and it is likely that higher flows will have been witnessed in the past. The flow on the Tyne is thought to be the highest since the Great Flood of 1771 (Environment Agency, 2016), which had an estimated flood peak of 3900m^{3}s^{-1} based on historical flood marks (Archer *et al*., 2007). Further work on pre-instrumental flood histories for other catchments would be needed to place the recent events in a multi-centennial context.

Many other catchments recorded new maximum peak flows for November, December, January or for any month. For some, these equated to events of exceptional rarity, with estimated return periods of more than 1-in-200 years (Table 2), including, for example, the rivers Dee (Scotland), Don, Cree, Wharfe and Calder, all of which correspond to areas impacted by flooding. Although the peak flows recorded on the Tay did not rank first for any of the winter months, daily flows exceeded 1000m^{3}s^{-1} on eight occasions in December–January, having only done so 35 times previously in the 64-year record.

The inherent difficulties in observing flows in the extreme high flow range – for example, due to non-modularity of flows, extrapolation of ratings or unmeasured bypassing at gauging stations – can lead to substantial uncertainty in the recorded peak flows. Furthermore, the geomorphological changes resulting from large-scale sediment and debris transport may have caused changes in the relationship between river levels and flows. As such, the peak flows and other hydrological variables presented in this paper should be viewed with caution and may also be subject to future review following detailed investigations of their accuracy.

Other hydrological responses

Groundwater

By late autumn 2015, groundwater levels were generally near or moderately below average, and seasonal recoveries had begun in parts of the far south of England. The most extreme rainfall that followed through winter 2015/2016 was focused across areas of northern and western regions of the UK where aquifer systems are less extensive but have larger capacities. As such, the extent to which groundwater was a factor in the winter 2015/2016 flooding was relatively limited.

Nevertheless, some boreholes in northern England, southern Scotland and Northern Ireland responded dramatically to the exceptional rainfall. In the Permo-Triassic sandstone of southwest Scotland (e.g. Newbridge; Figure 5(a)) and the fast-responding Chalk of eastern Northern Ireland (e.g. Killyglen), levels were notably high in November, and new maxima were established in December. Levels in Yorkshire also increased sharply in December to register as notably high in both the Chalk (e.g. Wetwang) and the Magnesian Limestone (e.g. Brick House Farm). Rising groundwater levels peaked in January; at Wetwang, levels were exceptionally high, and a new January maximum level was recorded at Brick House Farm in a 36-year series.

Although groundwater levels were exceptionally high at times in some parts of northern England, there were few reports of flooding solely from groundwater. In parts of the Jurassic Limestone of the North York Moors, sustained pumping of groundwater mitigated the threat of flooding. Nevertheless, aquifer outflows at Old Malton (North Yorkshire) supported high river levels, and groundwater added to flooding in river valleys in parts of northern Britain.

Once the unsettled weather had subsided, groundwater levels generally fell across northern England but remained above normal. As seasonal recessions began, levels remained in the normal range or above throughout the spring for the most of the UK. At Newbridge, levels continued to be exceptionally high throughout the spring and early summer (Figure 5(a)), in many months establishing new maxima in the period of record.

Table 2

New peak flow records[a] and return periods established in December 2015 or January 2016 for selected catchments in the UK (based on current best estimates). Return periods have been calculated using FEH methods as outlined in the text and have been placed into broad ranges.[b]

River	*Catchment area (km²)*	*Peak flow record start year*	*New peak flow (m³s⁻¹)*	*Return period of peak flow (yr)*	*Date*	*Rank in Dec/Jan*	*Pre-2016 max peak flow (m³s⁻¹)*	*Date*
Tweed at Norham	4390.0	1960	1361.0	10–25	5 Dec 2015	1	1965.2	Jan–2005
Mourne at Drumnabuoy House	1843.8	1982	925.5	25–50	5 Dec 2015	1	1063.9	Oct–1987
Tyne at Bywell	2175.6	1956	1730.0	100–200	5 Dec 2015	1[c]	1496.9	Oct–1967
Lune at Caton	983.0	1968	1740.0	100–200	5 Dec 2015	1[c]	1395.2	Jan–1995
Eden at Sheepmount	2286.5	1966	1680.0	>200	6 Dec 2015	1[c]	1516.4	Jan–2005
Dee (Wales) at New Inn	53.9	1969	98.0	10–25	12 Dec 2015	1	98.1	Nov–2009
Wharfe at Flint Mill Weir	758.9	1936	582.0	>200	26 Dec 2015	1[c]	417.3	Feb–1950
Calder at Mytholmroyd	171.7	1989	276.0	>200	26 Dec 2015	1[c]	191.9	Jun–2012
Irwell at Adelphi Weir[d]	559.4	–	–	–	26 Dec 2015	1[c]	–	–
Dee (Scotland) at Woodend	1370.0	1929	1362.5	>200	30 Dec 2015	1[c]	1132.5	Jan–1937
Cree at Newton Stewart	368.0	1963	476.2	150–250	30 Dec 2015	1[c]	375.0	Oct–2000
Tay at Ballathie	4587.1	1952	1811.0	25–50	4 Jan 2016	2	2267.9	Jan–1993
Don at Parkhill	1273.0	1969	728.3	>200	8 Jan 2016	1[c]	454.3	Nov–2002

[a]Peak flow data are limited to observations held on the National River Flow Archive and do not include pre-instrumental flow records.
[b]Note that there is no upper bound to the return period range of >200 years and that some return periods may be substantially higher.
[c]Denotes that the record established in December 2015/January 2016 was also the record for any month.
[d]Levels used to provide historical context due to uncertainty in the high flows. The Environment Agency confirmed the level is the highest on record.

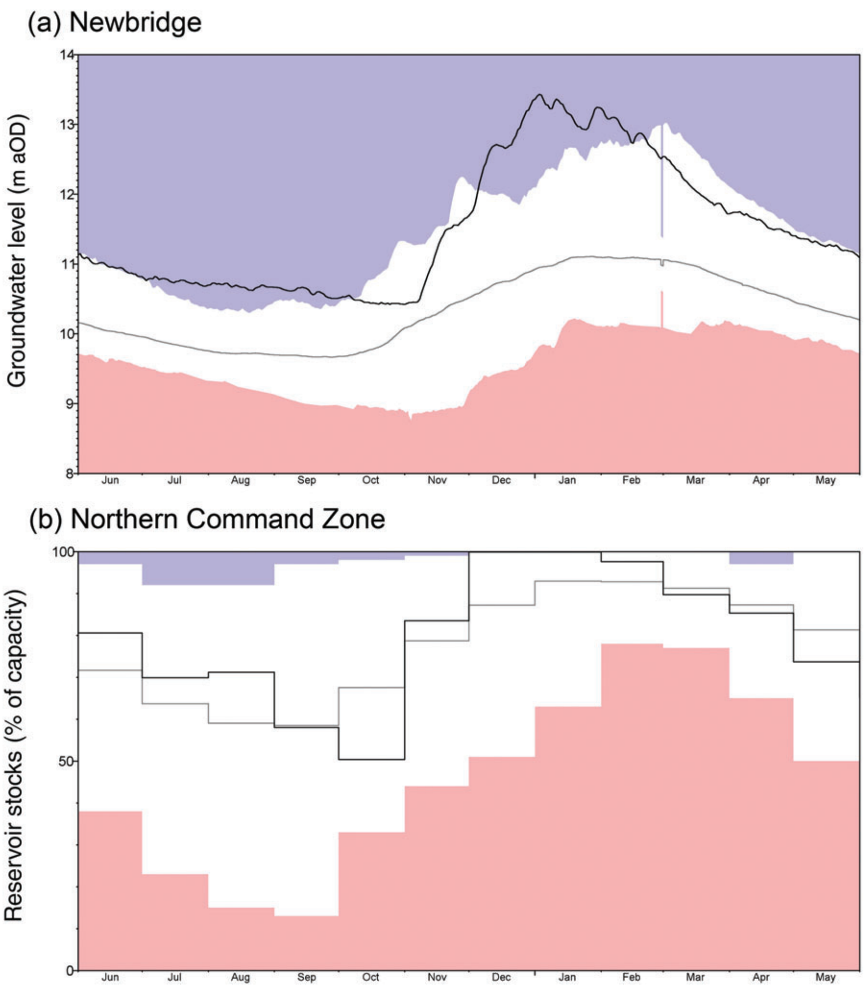

Figure 5. (a) Groundwater levels (m aOD) in a Permo-Triassic sandstone borehole at Newbridge for the period June 2015 to May 2016. (b) Reservoir stocks (% of capacity) for the Northern Command Zone reservoir group for the period June 2015 to May 2016. The long-term average is shown by the grey line. The blue and red envelopes show the highest and lowest levels/stocks on record, respectively.

Reservoirs

Dry conditions across the late summer and early autumn caused overall reservoir stocks for England and Wales to fall below average for the first time in more than a year by the end of October. Impoundments in northern and western Britain were particularly affected; several groups such as Elan Valley, Northern Command Zone and Derwent Valley were more than 15% below average.

Such shortfalls in reservoir storage were dramatically reversed by the very wet conditions that occurred during the November–January period. The most extreme rainfall occurred across upland areas of the north and west of the UK, causing reservoir stocks to increase sharply in the regions with reservoirs that most required replenishment. In northeast England, stocks increased by 44% in a week at Burnhope reservoir in response to Storm *Abigail* (Environment Agency, 2016). Kielder Water, the biggest reservoir in the UK by volume, also registered its second-largest weekly increase in stocks in a series from 1982 (Environment Agency, 2016). The transition in overall UK reservoir stocks between October and November was the third-largest monthly increase (for any month) in a record from 1995. By the end of November, stocks in most reservoirs were already above average, and further substantial rainfall in December and January pushed many impoundments close to capacity. Stored water in the Northern Command Zone doubled between October and December

(Figure 5(b)). Thereafter, stocks in northern and western parts of the UK remained close to capacity through the late winter and generally were near or above average throughout the spring, despite normal seasonal declines. In series from 1995, average reservoir stocks for the winter (December–February) for the UK overall were the second highest (after winter 2013/2014), and for Scotland were the largest on record.

Large reservoirs can make an important contribution to the amelioration of flooding, but only in those instances when the impoundment drains a sizeable proportion of the catchment upstream of at-risk urban areas. In northern and western Britain, where the impacts of rainfall and flooding in winter 2015/2016 were greatest, many reservoirs tend to be located in the upland areas of catchments, close to the source of the rivers. As such, despite below average stocks in the early autumn, this potentially useful mitigating storage was accounted for by the end of November following substantial rainfall. Nevertheless, the presence of Kielder Water was beneficial in slowing the flood peak from the North Tyne, causing it to lag behind that of the South Tyne (Environment Agency, 2016). Even with this beneficial reduction in peak flow on the Tyne, the gauging station at Bywell still registered one of the highest flows ever recorded in England and Wales; without Kielder Water, river flows would have been higher and more damaging.

Impacts

The winter storms caused substantial impacts across northern and western Britain and Northern Ireland. The period was defined by successive flooding episodes, with some communities being flooded multiple times. Around 16 000 properties were flooded in England in December alone, with more flooding in January (Hansard, 2016), compared to 8000 in the 2012 floods (Parry *et al*., 2013) and 7000 in the 2013/2014 winter floods (Muchan *et al*., 2015). All these events saw significantly fewer properties flooded than the 55 000 affected during the summer 2007 floods, an event that saw a far greater prevalence of urban surface water flooding (Marsh and Hannaford, 2007). A comparison of flood events by impacts is problematic due to a number of confounding factors, such as the presence/absence of flood defences, antecedent conditions and focal area. In 2015/2016 flooding was minimised by a network of defences that generally performed well, protecting 20 000 properties from flooding in England during December (Hansard, 2016). While there was some overtopping of defences, their efficacy provided sufficient time for residents to relocate possessions or be evacuated. Nevertheless, the spatial scale and the duration of flooding over winter 2015/2016 in northern and western regions of the UK caused considerable impacts on homes, businesses, industry, transport and agriculture. At the time of this article being prepared, the extent of impacts is still being evaluated – more comprehensive assessments will undoubtedly follow.

The focus of the flooding from Storm *Desmond* was in Cumbria, with Cumbria Police declaring a major incident on 5th December in response to the widespread flooding of properties and infrastructure. Carlisle was among the worst affected, with approximately 3500 properties flooded. Further east, the Tyne burst its banks in several locations in Northumberland, people were evacuated from their homes and strong winds left thousands of properties without power. Storm *Desmond* also caused impacts in Scotland: 1000 people were evacuated in Hawick as the Teviot flooded, and a major emergency was declared in Dumfries and Galloway as the Nith flooded properties. The worst of the flooding on Boxing Day was particularly focused in river basins draining the Pennines. As a result, major flooding affected large urban areas, including Manchester and Leeds, properties were also flooded in Ribchester and Whalley, including 2000 in Calderdale. Elsewhere in the region, 627 properties flooded in York; the number of properties affected would have been higher had the Foss Barrier not been raised. With the passage of Storm *Frank*, Scotland bore the brunt of the impacts, including widespread flooding in and around Aberdeen, landslips and power cuts. The impacts in Scotland continued into January, with substantial flooding in Inverurie on the 7th/8th and further flooding in Aberdeenshire.

Throughout the winter, flooding affected communities across northern and western Britain – notably so in some of the UK's major urban centres. Nearly 5000 businesses across Northumberland, Cumbria, Lancashire, Yorkshire and Greater Manchester were affected by the December storms, including the United Biscuits factory and the football stadium in Carlisle and the Jorvik Viking Centre in York. Substantial property flooding was also seen in Manchester, Leeds and York. There were, however, also impacts on smaller, rural communities. Agriculture suffered greatly from the winter storms – 2000 sheep were lost in Cumbria alone, cattle were swept downstream and there was extensive floodplain inundation causing damage to arable and pastoral land.

Flooding had substantial impacts on infrastructure, including power generation. Following Storm *Desmond*, 23 000 homes were without power in Northumberland, and 6000 homes suffered power cuts in Scotland during Storm *Frank*. In some cases, there were prolonged power outages as the water at flooded sub-stations needed to drain or be pumped away – thousands of properties in Yorkshire had no power for several days over the Christmas period. The protracted nature of the event had significant impact on transport links, as numerous roads and bridges were closed in northern Britain and Northern Ireland. Hundreds of bridges were damaged and several collapsed, notably in Tadcaster and Pooley Bridge, both eighteenth century structures. The destruction of roads and bridges caused long-distance diversions in some locations and took months to repair – in the Lake District the arterial A591 was closed after Storm *Desmond*, causing a 65 km diversion until repairs were completed in May 2016. Rail services were unable to run due to flooding and infrastructure damage, including the West Coast mainline north of Carlisle. There was also major damage to the Rochdale Canal, the Calder and Hebble Navigation, and the Aire and Calder Navigation on 26th December.

The flooding triggered a massive emergency response involving staff from the UK environmental agencies, emergency services and military personnel. Following a government COBRA meeting, hundreds of military personnel were mobilised between Christmas and New Year to aid civil and emergency services and clear-up operations in numerous locations across Cumbria, Lancashire, and North and West Yorkshire. At the time of writing, £200 million of additional investment has been pledged to aid recovery – £51 million for those affected by Storm *Desmond*, £40 million to Highways England for the repair and rebuilding of roads and bridges and £100 million for the Community Recovery Scheme to local authorities for affected homes and businesses, including grants to improve flood protection. A Farming Recovery Fund provided grants to farmers to help restore damaged agricultural land. Figures released by the Association of British Insurers (ABI) suggest that flood damage has resulted in claims for more than 16 000 properties, which are likely to lead to pay-outs of £1.3 billion (ABI, 2016). The average cost of each domestic claim is around £50 000, which is higher than previous events (ABI, 2016). Of course, like all floods, the winter 2015/2016 episode had a huge human toll, in terms of impacts on mental health, wellbeing and livelihoods that belies any straightforward economic assessment. While by summer 2016 recovery of infrastructure had progressed well, the impact of these events on individuals and communities is likely to be far-reaching and long-term.

Historical context and trends

As the preceding sections illustrate, the winter 2015/2016 was an extreme hydrological episode, in terms of magnitude, duration, spatial extent and impacts. That the 2015/2016 winter follows only 2 years after the protracted winter flooding of 2013/2014 (Muchan *et al*., 2015) is all the more remarkable. These winters were the wettest two on record for the UK as a whole (in records from 1910; McCarthy *et al*., 2016). In terms of runoff, these episodes stand out together in the Great Britain outflow series (Figure 6).

Moreover, these events add to an apparent cluster of flood events in the early twenty-first century. Severe flooding also occurred in 2012; while less exceptional in terms of winter outflows, over shorter periods outflows were also exceptional, and flooding was also witnessed in the summer of that year (Parry *et al*., 2013). Other national scale flood events have also occurred since the turn of the millennium (e.g. 2000/2001, 2007; see Table 2 in the review of Hannaford (2015) and references therein). Recent years have also seen other regional flood events that have impacted the areas of northern Britain affected in winter 2015/2016. Cumbria, for example, experienced devastating flooding in 2005 and 2009 (Miller *et al*., 2013). Peak flows for the former were the highest on record for England, while the latter event resulted in a 24h rainfall record – records which were eclipsed by Storm *Desmond* in December 2015. This apparent prevalence of flood events has inevitably led to speculation that flooding is increasing in the UK.

While there are substantial uncertainties in scenario-based climate change projections for UK future flood risk, expectations are for an increase in flood severity in many areas, especially in the winter (see the review of Watts *et al.* (2015) and references therein). The question of whether recent floods are evidence of these increases becoming manifest is a more challenging one. The UK has become significantly warmer over the last few decades, and the link with anthropogenic emissions is unequivocal. The extent to which this has influenced flooding requires an investigation of long records of rainfall and river flow. There is mounting evidence for an increase in heavy rainfall in the UK over recent decades (Jones *et al*., 2013), but increases in rainfall do not necessarily equate to equivalent increases in flooding. A great deal of research has examined long-term trends in river flooding in the UK (see the review of Hannaford, 2015). In general, the work concludes that there is little compelling evidence for any upward trend in long records of flood magnitude or frequency in the UK. However, the north and the west of the UK has seen an increase in winter runoff and high river flows since the early 1960s, associated with changes in atmospheric circulation patterns. This is particularly the case with the North Atlantic Oscillation (NAO), which in its positive state, as it was in 2015/2016, results in milder, wetter winters in the northwest.

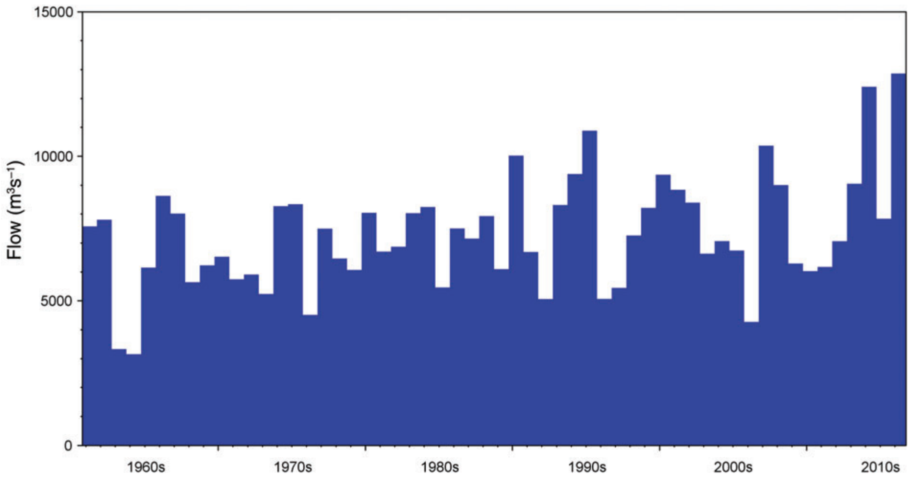

Figure 6. Average winter (December–February) outflows (m^3s^{-1}) for Great Britain 1961–2016.

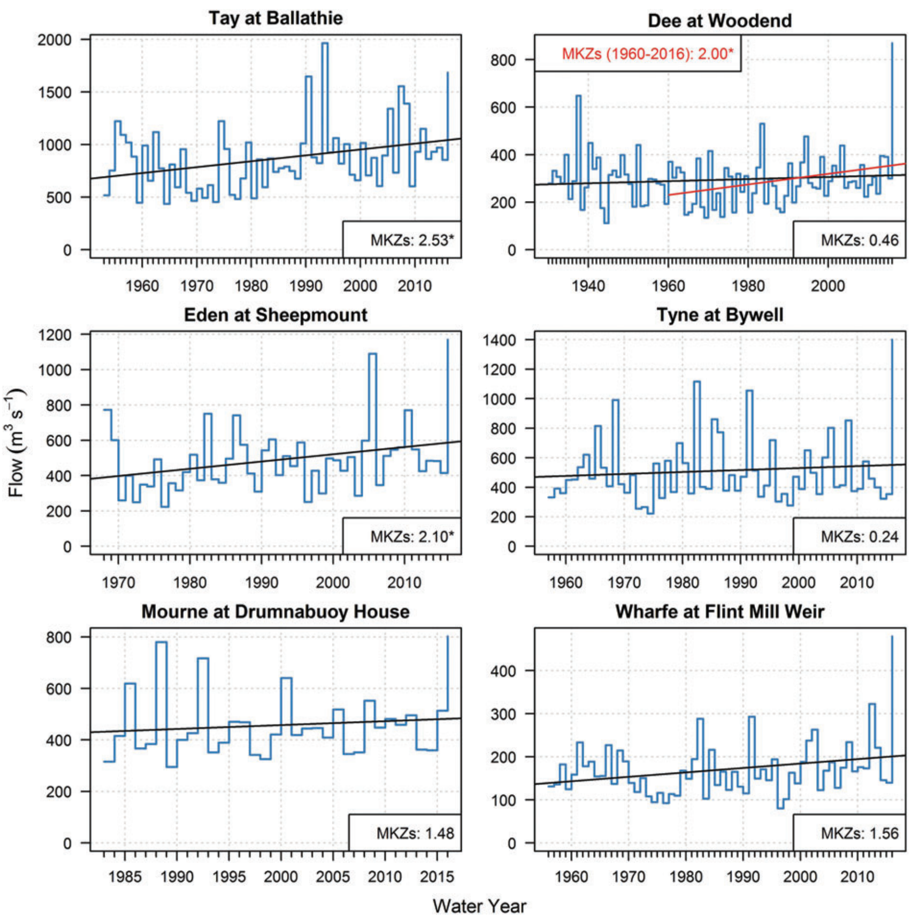

Figure 7. Trends in annual maximum daily flow (water years). Note that water year 2015/2016 includes data up to 30 June 2016 only. Trend lines (solid black) given by linear regression and evidence of monotonic trend by the non-parametric Mann-Kendall (MK) test. The standardised MK statistic (MKZs) is positive (negative) with an increasing (decreasing) trend, and statistically significant at the 5% level when |MKZs|>1.96, denoted by (*). For comparison, the trend over water years 1960–2016 is also estimated for the Dee at Woodend (solid red line).

Much of the published research reviewed in Hannaford (2015) used records up to the early years of the millennium (latest date 2008), thereby preceding some of the most severe flood events of the last decade. Detailed up-to-date national scale trend analyses have yet to be published, but Figure 6 suggests that a tendency towards increasing winter runoff has continued. Up-to-date assessments of annual maximum peak flow trends (in this case based on daily data, as instantaneous peaks are not yet widely available) are presented in Figure 7, for the same six catchments as in Figure 3. As well as further demonstrating the exceptional nature of the winter 2015/2016 peak, the plots show statistically significant increases from around the 1960s on the Tay and the Eden (the most 'westerly' influenced catchments), as well as increases over a similar period for the Wharfe and Tyne (eastward flowing catchments with headwaters in northwest England).

While trends in high flows can be recognised, it is not clear to what extent the recent clustering of floods in upland Britain, or anywhere else, are associated with climate change, natural variability or – as is intuitively most likely – a combination of both. Most UK river flow records are relatively short, commencing in the 1960s or later. The Scottish Dee is a rare example of a long record (from 1929), and Figure 7 demonstrates that the long-term trend is far less steep and is non-significant when compared to a trend from the 1960s. Many previous studies (see references in Hannaford, 2015) have pointed to pronounced inter-decadal variability, leading to 'flood rich' and 'flood poor' periods driven by the NAO and other factors. For the Eden, such periods have been identified in records back to 1770 (Pattison and Lane, 2012). It is, therefore, hard to attribute any event or cluster of events to anthropogenic climate change using observational records alone.

There is a growing literature on formal 'detection and attribution' studies that use sophisticated modelling techniques to attribute the anthropogenic forcing component of extreme events. Following the widespread flooding in autumn 2000, research showed these events were made more likely because of human influence on the climate (Kay *et al*., 2011; Pall *et al*., 2011). A similar study for the winter 2013/2014 floods (Schaller *et al*., 2016) concluded the exceptional winter rainfall was made significantly more likely, and also attributed an increased risk of high flows and property damage on the lower Thames to anthropogenic warming – although these effects were more modest. A 'real-time' attribution study was presented within a week of the early December 2015 flooding, claiming that the Storm *Desmond* rainfall was made 40% more likely as a result of anthropogenic warming (van Oldenborgh *et al*., 2015). However, this was based on very preliminary data; future studies will no doubt be published which build on this approach.

While it is very challenging to identify and attribute long-term trends in flooding, the extreme variability seen in the early twenty-first century, coupled with an increasing confidence in event attribution studies, strengthens the argument that we are seeing emerging evidence of anthropogenic warming on high flow regimes in the UK. Quantifying this effect remains a crucial topic for further research. Irrespective of the anthropogenic contribution, recent floods have extended the range of recorded variability, with significant implications for flood risk management. Understanding this variability and its causes is an important foundation for identifying appropriate responses.

Concluding remarks

There have been a number of exceptional, high profile flood events in the early years of the twenty-first century and, as such, flooding has become a subject of intense public, political and media debate. While many of these events have warranted the label of 'unprecedented' to some degree (whether in terms of flow magnitude, duration, spatial extent etc.), there is no close modern parallel to the events of winter 2015/2016. As an individual event, Storm *Desmond* exceeded the previous regionally significant events of 2005 and 2009. The flooding around Boxing Day was the most severe on record in many major rivers of northern England. Similarly, parts of Scotland saw damaging and record-breaking flooding in January. Each of these events was exceptional; their clustering over a 4-week period has arguably set a new benchmark in terms of flood severity, at least in the timeframe of typical gauging station records extending back 40-50 years. Of course, fuller historical appraisals using pre-instrumental records would be needed for a wider historical context. Coupled with other instances of repeated severe flooding (e.g. in 2007, 2012, 2013/2014), the winter of 2015/2016 further highlights the vulnerability of the UK to persistent episodes of severe storminess.

This paper has provided a description of these events, their severity and their impacts, and has also considered the historical context and recent hydrological variability. As with the 2013/2014 floods, these events were intensely politicised and the subject of rolling media coverage. They triggered debates on climate change, flood protection measures, governance of flood management and flood defence spending, amongst many other dimensions. A particular focus of the discourse in winter 2015/2016 was around the impact of land use/land management upon flooding and on the utility of the 'natural flood management' paradigm. A heightened profile of flooding issues, and a more open debate of these various solutions, is welcome, although it is unlikely that such measures would have made a significant difference beyond the very local scale given the sheer scale and rarity of the triggering rainfall. Many previous studies (e.g. the review of O'Connell *et al*., 2007) have shown that land use and management impacts on flooding are typically only detectable at small catchment scales or for relatively low magnitude events. Nevertheless, in circumstances where even a modest reduction in peak flow would have had an obvious beneficial effect, the full range of mitigation strategies clearly needs to be considered. An important avenue for future research is in identifying the optimal balance and configuration of various strategies in different UK contexts. In this regard, the flooding prompted a number of major reviews, including a national resilience review (DEFRA, 2016) that seeks to assess how the UK can improve protection from extreme weather in future.

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