National Hydrological Monitoring Programme

The winter floods of 2015/2016 in the UK
- a review

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Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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THE WINTER FLOODS OF 2015/2016 IN THE UK – A REVIEW

This report was produced by the Centre for Ecology & Hydrology (CEH), the UK's centre for excellence for research in land and freshwater environmental sciences, in collaboration with the British Hydrological Society (BHS) which promotes all aspects of the inter-disciplinary subject of hydrology – the scientific study and practical applications of the movement, distribution and quality of freshwater in the environment. Funding support was provided by the Natural Environment Research Council.

CEH and BHS are extremely grateful to the many individuals and organisations that provided data and background information for this publication. River flow and groundwater data were provided by the principal hydrometric measuring authorities in the UK: the Environment Agency in England, the Scottish Environment Protection Agency, Natural Resources Wales (Cyfoeth Naturiol Cymru) and the Rivers Agency in Northern Ireland. The Met Office National Climate Information Centre (NCIC) supplied the majority of the rainfall and climatological data featured in the report[a]. The reservoir stocks data were provided by the water service companies, Scottish Water and Northern Ireland Water. Additional data and information has been provided by the Canal & River Trust and a range of individuals and organisations. The provision of the basic data, which provides the foundation both of this report and the wider activities of the National Hydrological Monitoring Programme (NHMP), is gratefully acknowledged.

Note: as is the case with the documenting of most extreme hydrometeorological episodes a proportion of the data featured in this report – maximum river flows in particular – is necessarily provisional and may be subject to future revision.

The National Hydrological Monitoring Programme

This report is an output from the NHMP which is operated jointly by CEH and the British Geological Survey (BGS). The NHMP was set up in 1988 and aims to provide an authoritative voice on hydrological conditions throughout the UK and has a particular obligation to document major contemporary hydrological events and to identify and interpret long-term hydrological change and variability. Monthly Hydrological Summaries for the UK are routinely published as part of this programme.

This document, and a full set of the publications in the NHMP series, including the monthly Hydrological Summaries, are available from the NHMP website: http://nrfa.ceh.ac.uk/nhmp.

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INTRODUCTION

A remarkably persistent and exceptionally mild cyclonic episode beginning in early-November 2015 and lasting around fourteen weeks brought severe, extensive and protracted flooding which impacted most damagingly on northern Britain, Northern Ireland and parts of Wales. Many existing rainfall and seasonal temperature records were eclipsed during this period and, most notably, maximum recorded river flows were exceeded over a substantial proportion of the country. At the national scale, previous maximum daily and monthly outflows were clearly eclipsed and four relatively discrete episodes of extreme runoff can be recognised. In many areas, the magnitude, persistence and repetitive nature of the flooding had major adverse impacts on communities, infrastructure, agriculture and a host of other sectors of the economy.

The extent and duration of the flooding has very few close parallels in the historical record and, overall, it was a hydrometeorological episode which ranks alongside the 1975/1976 drought and 1947 floods as the most extreme broad-scale events captured in observational records during the last 100 years at least. The truly exceptional runoff patterns experienced in 1947 and 1976 had a major impact on flood and drought management strategies but occurred before the exacerbating impact of climate change was generally recognised. The 2015/2016 flooding, together with the impact of other protracted flood events in the 21st century thus far, has underlined the need to adapt engineering design and flood management strategies to accommodate the recent extension in the range of recorded runoff variability.

This report documents the 2015/2016 flooding within a hydrometeorological framework. The extreme conditions are reviewed in the context of lengthy rainfall and river flow time series, and a brief review is included of their magnitude relative to other major flood episodes. In addition, rainfall and river flow patterns through the early part of the 21st century are examined within the context of hydrological trends emerging over the post-1960 period.

METEOROLOGY OF WINTER 2015/2016

Climatological and physical background

The UK is exceptionally diverse in terms of its climate, geology and land use. Each, to differing degrees, can influence vulnerability to flooding. The climate is temperate and, whilst notably capricious in the short term, sustained periods of very dry or very wet weather are relatively rare. Rainfall across the UK derives predominately from Atlantic low pressure systems and on average, is well distributed throughout the seasons but with a tendency towards an autumn and early winter maximum, particularly in western areas. By contrast, spatial variations in rainfall are large; the annual average in the wettest upland areas, mostly in the west, is around six times greater than in the driest areas of the eastern lowlands. Aside from a few mountainous regions, the Cairngorms in particular, snow is generally a very minor component of total precipitation but snowmelt can be an important exacerbating factor in relation to flood risk, particularly across northern Britain. Historically, snowmelt has contributed to a substantial number of major floods events throughout the UK.

At a national scale, around half of the annual rainfall is accounted for by evaporation losses which peak during the late spring and summer. Evaporation demands are typically of minor significance in moderating any particular flood episode, but primarily through their impact on antecedent soil moisture conditions, they exercise an important control on flood seasonality. Whilst intense rainfall can produce flash flooding in any season, the frequency of fluvial flooding is much greater during the winter half-year with around 80% of major events occurring within the October-March timeframe. However, extreme flow events do occur during the summer half-year (for example in 2007[1]) particularly in upland and urban catchments.

The 2015/2016 flooding generally had its greatest impact in those northern and western parts of the UK which are characterised by relatively steep slopes, high rainfall and thin soil cover. A proportion of the more extreme flows occurred in sparsely populated areas but with the terrain restricting most large settlements to the lower valleys, urban flooding was severe and, in many areas, repetitive.

Rainfall

Synoptic background

The early autumn of 2015 was notably dry across much of the country – the combined September and October rainfall was the third lowest for the UK since 1914. However, from early-November 2015, a persistent sub-tropical airflow from the south-west became established and dominated weather conditions until well into the following February[2]. Crucially, in relation to the flooding, the Jet Stream guided a succession of very vigorous low pressure systems along similar south-west to north-east tracks across the UK. This synoptic pattern coincided with above average sea surface temperatures, a strongly positive phase of the North Atlantic Oscillation and a strong El Niño (other teleconnections will also have been influential). These driving mechanisms provided the backcloth to a 14-week period that was truly remarkable in both meteorological and hydrological terms[3,4,5] – many existing rainfall and temperature records were exceeded and, in relation to runoff patterns, this episode has very few close historical precedents.

Several of the major flood events were associated with named storms (Table 1). The naming of storms was introduced in September 2015 by the Met Office and Met Éireann to designate those expected to cause disruptive impacts in the UK, to raise awareness of severe weather and improve

Table 1 *Named storms in the winter of 2015/2016. Those with the greatest hydrological impacts are marked in bold.*

Source: Met Office Storm Centre.

Name	Date of impacts (UK/Ireland)
Abigail	**12th - 13th November**
Barney	17th - 18th November
Clodagh	29th November
Desmond	**5th - 6th December**
Eva	24th December
Frank	**29th - 30th December**
Gertrude	**29th January**
Henry	1st - 2nd February
Imogen	8th February
Jake	2nd March
Katie	27th - 28th March

public safety. From a hydrological perspective, it should be noted that forecast wind speed is the primary criterion for such designations. For some, Storm Eva for example, the associated wind damage was much more significant than its contribution to flooding. Conversely, some major flood events, particularly those around Boxing Day 2015, followed unnamed storms. Whilst few of the low pressure systems brought exceptional rainfall to the English Lowlands, flood-generating storms were experienced from south-west England to the north of Scotland.

The following paragraphs provide a monthly commentary on the rainfall patterns between November 2015 and February 2016. More detailed information relating to national and regional rainfall totals across a range of timespans is given in Table 2, whilst Figure 1 illustrates the monthly rainfall for individual months and for the November to January period – which best captures the regional footprint of the most severe flooding.

November

After a dry start, November was notably mild and dull as the passage of several deep Atlantic low pressure systems effected a dramatic transformation. A 24-hour rainfall total of 78mm was recorded on Skye on the 8th and further exceptional totals were registered, particularly over western hills, during the passage of Storm Abigail in the second week. Mid-November rainfall accumulations included three-day totals of 94mm at Eskdalemuir (Dumfries and Galloway) and 138mm at Shap (Cumbria) whilst in Snowdonia the Capel Curig raingauge recorded 285mm over six days to the 11th and another 63mm on the 15th. Synoptic patterns remained very unsettled to month-end, although a brief interlude dominated by a northerly airflow brought modest snowfall to many parts of the UK on the 22nd. However, snow accumulations generally only made a minor contribution to flood risk throughout most of the winter.

The dominance of cyclonic conditions ensured that regional rainfall totals for November were markedly high in a broad zone from mid-Wales to central Scotland (Figure 1a). Much of northern England, Wales and southern Scotland registered more than twice the long-term monthly average rainfall and North West England registered its second wettest November (after 2009) in a series from 1910. Conversely, as most low pressure systems followed a similar track across the country below average rainfall was recorded in southern and eastern England and north-east Scotland.

December

December was even more cyclonic than November and was an extraordinary month in both meteorological and hydrological terms. Whilst November temperatures and rainfall were certainly unusual, those for December were extreme. During the first week, Storm Desmond brought heavy and persistent rainfall across much of northern Britain, where enhanced by substantial orographic uplift, many storm totals were outstanding. In the northern Pennines, 179mm was recorded over 36 hours at Garrigill Noonstones Hill whilst much of the central fells of Cumbria registered >200mm in 38 hours[4]. At Honister Pass (Plate 1), a new 24-hour rainfall total for the UK of 341.4mm was recorded. Provisional estimates using the revised Flood Estimation Handbook rainfall frequency model[7] suggest this total has a return period in excess of 1-in-1,000 years. At nearby Thirlmere, a total of 405mm eclipsed the previous 48-hour maximum for the UK. These outstanding totals caused severe flooding in parts of Cumbria (see page 22). Rainfall was generally less intense in Scotland, but a 137mm total was recorded over 34 hours in the headwaters of the Teith catchment, with a similar total reported from Glen Nevis (Highlands).

The Christmas period was also outstandingly wet in many northern and western areas. The passage

Plate 1 *Raingauge at Honister Pass (Cumbria).*
Photo: Harvey Rodda, Hydro-GIS.

Table 2 *National and regional rainfall totals and associated return periods for selected durations during the November 2015 - February 2016 period.*

Region	Rainfall	Nov 2015	Dec 2015	Jan 2016	Nov 15 - Dec 15	RP	Nov 15 - Jan 16	RP	Nov 15 - Feb 16	RP
United Kingdom	mm	173	219	180	392		571		686	
	%	151	182	153	167	>100	164	>>100	158	>>100
England	mm	118	134	125	252		376		450	
	%	144	151	151	148	10-20	150	30-50	146	40-60
Scotland	mm	242	328	254	570		823		995	
	%	151	204	154	178	>>100	170	>>100	165	>>100
Wales	mm	246	335	244	581		824		979	
	%	161	203	160	183	80-120	178	>>100	171	>>100
Northern Ireland	mm	191	220	176	411		586		695	
	%	173	187	147	180	>>100	171	>>100	162	>>100
England & Wales	mm	135	162	141	297		438		523	
	%	148	163	153	156	20-30	157	80-120	151	60-90
North West	mm	261	335	187	596		783		925	
England	%	209	255	154	233	>>100	210	>>100	202	>>100
Northumbria	mm	159	225	174	385		558		621	
	%	191	262	213	227	>>100	225	>>100	202	>>100
Severn-Trent	mm	98	111	95	209		304		376	
	%	138	139	128	138	5-10	163	8-12	136	10-15
Yorkshire	mm	152	169	123	321		444		519	
	%	193	189	152	191	>100	181	>100	171	>100
Anglian	mm	67	54	68	121		190		223	
	%	118	97	128	108	2-5	114	2-5	109	2-5
Thames	mm	73	73	94	146		240		295	
	%	110	100	137	105	2-5	116	2-5	117	2-5
Southern	mm	82	84	149	167		316		366	
England	%	99	96	180	97	2-5	126	2-5	120	2-5
Wessex	mm	91	96	130	187		317		405	
	%	105	94	140	99	2-5	114	2-5	117	2-5
South West	mm	157	169	223	326		549		686	
England	%	118	113	158	115	2-5	131	8-12	131	10-15
Welsh	mm	228	317	234	545		779		926	
	%	156	201	160	179	70-100	176	>>100	169	>>100
Highland	mm	260	365	249	625		873		1081	
	%	129	184	124	156	>100	146	60-90	145	80-120
North East	mm	95	192	231	287		519		591	
Scotland	%	95	211	237	151	10-20	182	>100	169	>100
Tay	mm	217	367	331	583		915		1049	
	%	165	260	211	214	>100	215	>>100	197	>>100
Forth	mm	236	296	220	531		751		889	
	%	206	240	173	223	>>100	207	>>100	169	>>100
Tweed	mm	203	281	225	484		708		810	
	%	216	270	224	244	>>100	240	>>100	222	>>100
Solway	mm	281	375	262	656		919		1107	
	%	189	233	169	212	>>100	200	>>100	193	>>100
Clyde	mm	350	373	272	723		995		1107	
	%	187	190	135	189	>>100	171	>>100	169	>>100

% = percentage of 1971-2000 average *RP = Return period*

Note: *the return period estimates[6] are based on monthly data provided by the Met Office and reflect climatic variability since 1910; they also assume a stable climate. Data since February 2016 (inclusive) are provisional. The quoted return periods relate to the specific timespans only; for the same timespans, but beginning in any month the return periods would be substantially shorter. For regional boundaries see the Location Map (page 33).*

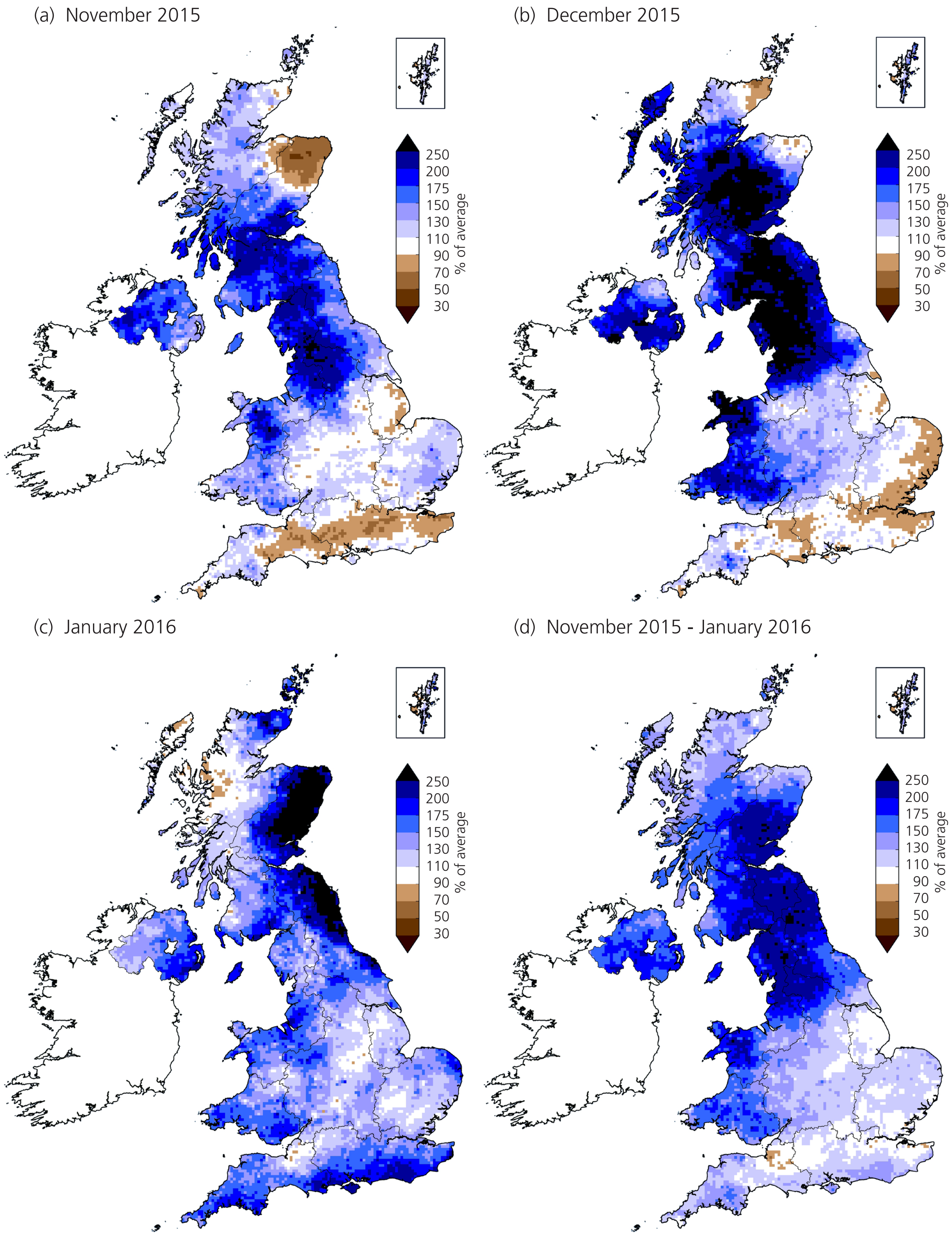


Figure 1 *Rainfall anomaly maps (% of 1971-2000 average) for the November 2015 - January 2016 period.*

of Storm Eva brought damaging winds but limited rainfall across the country, but another deep depression on Boxing Day was accompanied by heavy and sustained rainfall. Notable storm totals were registered in many localities across northern England and Wales. At Capel Curig (Snowdonia), a total of 214mm was recorded over the 26th and 27th, whilst in West Yorkshire a 36-hour total of 126mm was registered for Gorpley and totals >100mm were common in headwaters draining the southern Pennines[2]; notable 48-hour totals were also recorded in the east of the county (e.g. in parts of the North York Moors and in the Foss catchment)[8]. The consequent flooding across northern England was severe and sustained (see page 23). Less than a week later, on the 29th/30th, Storm Frank brought significant rainfall totals to parts of northern Britain. Scotland was a particular focus, with notable totals including 80mm at Tyndrum (Perthshire).

The continuing passage of vigorous frontal systems ensured that longer term rainfall accumulations were also outstanding in many areas. Across much of the uplands of Cumbria, northern Pennines and the Cairngorms, December rainfall totals exceeded three times the 1971-2000 average (Figure 1b) and, despite below average monthly rainfall in some areas (e.g. parts of East Anglia), the monthly rainfall total for the UK marginally exceeded November 2009 as the wettest month in a series from 1910. A new any-month maximum was also established for Scotland, eclipsing the previous record by around 50mm. For Wales, only November 1929 was wetter – and then only marginally so – and, in Northern Ireland, the December rainfall total closely approached the previous monthly maximum. At a regional level across the UK, the margins by which previous maxima were exceeded were often substantial. For a region embracing North West England and North Wales, the December rainfall was truly exceptional (Figure 2), more than

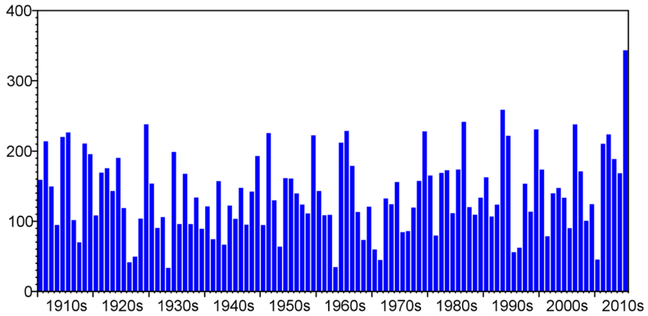


Figure 2 *December rainfall totals (mm) for North West England and North Wales.*

30mm greater than the previous maximum for any month. An extended historical perspective is provided by the monthly Central Lake District rainfall series[9] which begins in 1788; the December of 2015 registered as the wettest December on record by a considerable margin, and was the second highest, after November 2009, for any month[b].

January

In most regions, January rainfall totals were considerably lower than those for December (Table 2) but weather patterns remained very cyclonic, particularly early and late in the month. In Scotland, the first week was particularly wet, with several days of notable rainfall totals. On the 3rd, 104mm was recorded at Spittal of Glenmuick (Aberdeenshire) and on the 3rd/4th a 77mm 48-hour total was recorded at Aboyne (Aberdeenshire). Notable 48-hour totals were also registered on the 7th/8th in many areas, including at Aberdeen Airport which recorded 75mm. As a result, some parts of north-east Scotland recorded their monthly average rainfall in the first week. The final week, which included the passage of Storm Gertrude, brought further very high rainfall accumulations; 72-hour totals included 160mm at Capel Curig, 106mm at Eskdalemuir, and 100mm on the Isle of Skye.

Although significant parts of the English Lowlands received less than the average monthly rainfall, the UK total still ranked among the ten wettest Januarys on record with a large majority of the country registering 50% or more above the long-term average (Figure 1c). Eastern Scotland was particularly wet with many regions recording more than twice the long-term average. For the Tweed region, the previous highest January rainfall total was exceeded and parts of Aberdeenshire were exceptionally wet also. The more varied tracks of the low pressure systems in January, and the associated heavy rainfall, triggered Flood Alerts in many parts of the country and, as in the preceding two months, pluvial flooding was common. Whilst the seasonally very mild conditions meant that snowmelt was not a significant causative factor in the November and December flooding, it did contribute to the exceptional runoff episodes in Scotland particularly in rivers draining the Cairngorms.

[b]The December 2015 total is under review; it may be revised upwards to account for raingauge overflow.

February

February was the driest of the winter months with much of eastern Britain recording well below average rainfall. However, notably wet conditions continued in many of the flood-stricken western areas, particularly early in the month. Storm Henry brought gale force winds and heavy rainfall to north-west Britain on the 1st/2nd – in Wester Ross, daily rainfall totals of 60mm and 95mm were recorded at Cluanie Inn and Kinlochewe respectively. A week later the passage of Storm Imogen resulted in further significant rainfall; daily totals of >50mm were common in south-west England and, again, around mid-month in Cumbria. Over the hills of eastern Scotland a significant proportion of the precipitation fell as snow and high winds contributed to substantial drift accumulations. From around mid-month however, synoptic patterns became much more settled with high pressure over the North Atlantic bringing a colder, drier airflow across most of the UK. Despite limited precipitation over the final fortnight, February rainfall totals were well above average from north Wales to western Scotland; regional totals for North West England, Solway and Clyde each exceeding 160% of the 1971-2000 average.

Raingauge, regional and national rainfall

Rainfall totals at the local, regional and national scales were extreme across a wide span of timeframes through the late autumn and winter of 2015/2016. Table 3 gives selected rainfall accumulations for five raingauges and confirms the primacy of the 2015/2016 wet episode: each of the raingauges in Table 3 established new period of record maxima in the 60-day timeframe and previous maxima across a range of timespans were often exceeded by appreciable margins. The first three featured raingauges in Table 3 are located in north Wales and Cumbria which are among the wettest parts of the UK and notable rainfall totals extending over substantial areas are certainly not rare[10]. Nonetheless, the rainfall accumulations which generated and sustained the winter flooding were extreme. In Snowdonia, the Capel Curig raingauge recorded around 1,700mm in the 52 days ending on 27th December – approaching twice the annual average rainfall for England and Wales.

For the UK, the November 2015 - January 2016 rainfall established a new maximum for that timespan (Figure 3) and, more notably, for any three-month timespan in the NCIC series (Table 4). Over four months, the November - February total closely equates to the previous maximum (October 1929 - January 1930). Scotland also registered new rainfall maxima for sequences

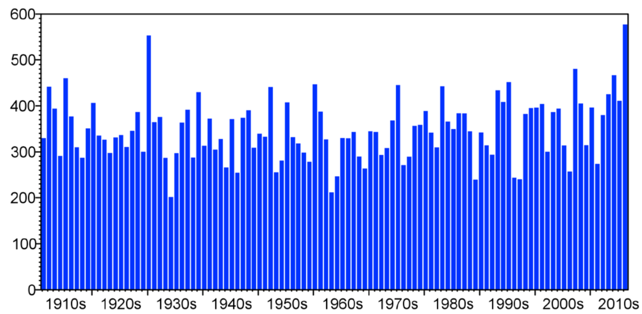


Figure 3 *November - January rainfall total (mm) for the UK.*

Table 3 *n-day maximum rainfall totals recorded during the winter of 2015/2016 together with their ranking.*
Data: NCIC, Met Office.

Raingauge	Start of record	1-day			30-day		60-day		100-day	
		Total (mm)	Date	Rank	Total (mm)	Rank	Total (mm)	Rank	Total (mm)	Rank
Cwmdyli (N Wales)	1921	138	25th Dec	7th	1054	1st	1709	1st	2459	1st
Dalehead (Cumbria)	1961	213	5th Dec	1st	974	1st	1644	1st	2128	1st
Seathwaite (Cumbria)	1961	208	14th Nov	2nd	1170	1st	1391	1st	2457	1st
Balmoral (NE Scotland)	1918	48	29th Dec	8th	300	2nd	428	1st	546	3rd
Eskdalemuir (SW Scotland)	1910	72	4th Dec	10th	577	1st	983	1st	1409	1st

Note: *most series contain some record gaps.*

Table 4 *Ranked 2- and 3-month rainfall totals (mm) for the UK.*

Rank	2-month period	Total (mm)	3-month period	Total (mm)
1	Nov 1929 – Dec 1929	400	Nov 2015 – Jan 2016	591
2	Dec 2015 – Jan 2016	398	Nov 1929 – Jan 1930	553
3	Dec 2013 – Jan 2014	376	Dec 2013 – Feb 2014	545
4	Oct 2000 – Nov 2000	367	Oct 2000 – Dec 2000	519
5	Jan 1990 – Feb 1990	353	Oct 1954 – Dec 1954	491
6	Oct 1954 – Nov 1954	353	Dec 1994 – Feb 1995	484
7	Dec 1994 – Jan 1995	346	Nov 2006 – Jan 2007	480
8	Nov 1914 – Dec 1914	342	Dec 1989 – Feb 1990	471
9	Nov 1986 – Dec 1986	339	Sep 1935 – Nov 1935	470
10	Dec 1993 – Jan 1994	336	Dec 1914 – Feb 1915	462

Note: *Periods are non-overlapping.*

of 1-4 months, as did Northern Ireland with the exception of the single-month maximum. Relatively dry conditions across many central, southern and eastern areas resulted in rainfall totals for England being less extreme. Nonetheless, the November-January rainfall was the third highest on record, and rainfall totals for northern England were remarkable. For North West England, the previous highest for that timespan was exceeded by more than 20% and, in Scotland, the corresponding margin for the Tweed basin exceeded 60% – an exceptional outlier. Many regional 3- and 4-month rainfall accumulations within the November-February timespan have associated return periods of well over 100 years (Table 2) – an important caveat is that the quoted return period estimates assume a stable climate.

At a national scale, there are no close parallels to the hydrometeorological conditions experienced through late 2015 and early 2016 although mild and wet conditions did characterise the late autumn/winters of 2013/2014, 2006/2007 and 1929/1930. Prior to 1910, exceptional 3-month rainfall totals for England and Wales, mostly in the winter months, were recorded in 1903, 1882, 1876, 1872, 1852 and 1829[11]. A cluster may also be recognised in the late 18th century but the sparse nature of the raingauge network and the higher proportion of snow in precipitation totals limits the accurate assessment of areal accumulations from this period.

Temperatures

The dominance of a mild tropical maritime airflow ensured seasonally remarkable temperatures throughout most of the late 2015 and early 2016 period. For the UK, November was the third warmest in the NCIC series but was clearly eclipsed by December. Overcast conditions resulted in seasonally extreme night-time temperatures throughout the month[2] and, remarkably, no air frosts were recorded across most of southern Britain. Correspondingly, the December mean temperature of 9.7°C was the highest on record for the UK by a substantial margin. Provisional data indicate that the mean temperature for the month was similar to the long-term average for April. The previous maximum December average in the Central England Temperature series (from 1659[12]) was exceeded by an extraordinary 1.6°C (Figure 4).

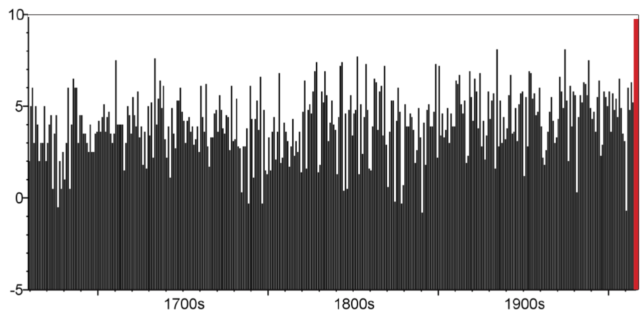


Figure 4 *December Central England Temperature (°C) from 1659. December 2015 is shown in red.*

Data: Climate Research Unit, University of East Anglia.

The mildness of the early winter in particular was reflected in generally vigorous grass growth and the exceptionally early appearance of spring flowers in many areas.

The inherent variability of the British climate, together with a judicious selection of regional coverage and/or the timeframe adopted, can easily serve to exaggerate the extreme nature of any particular climatological episode. However, the singularity of the conditions experienced through the late autumn and early winter of 2015/2016 is emphasised by Figure 5. A general association between higher temperatures and higher rainfall totals is evident and the frequency of wet and mild winters is greater in the recent past compared with much of the 20th century. Even within that context though, the November to January period in 2015/2016 is clearly an outlier in relation to both temperature and rainfall.

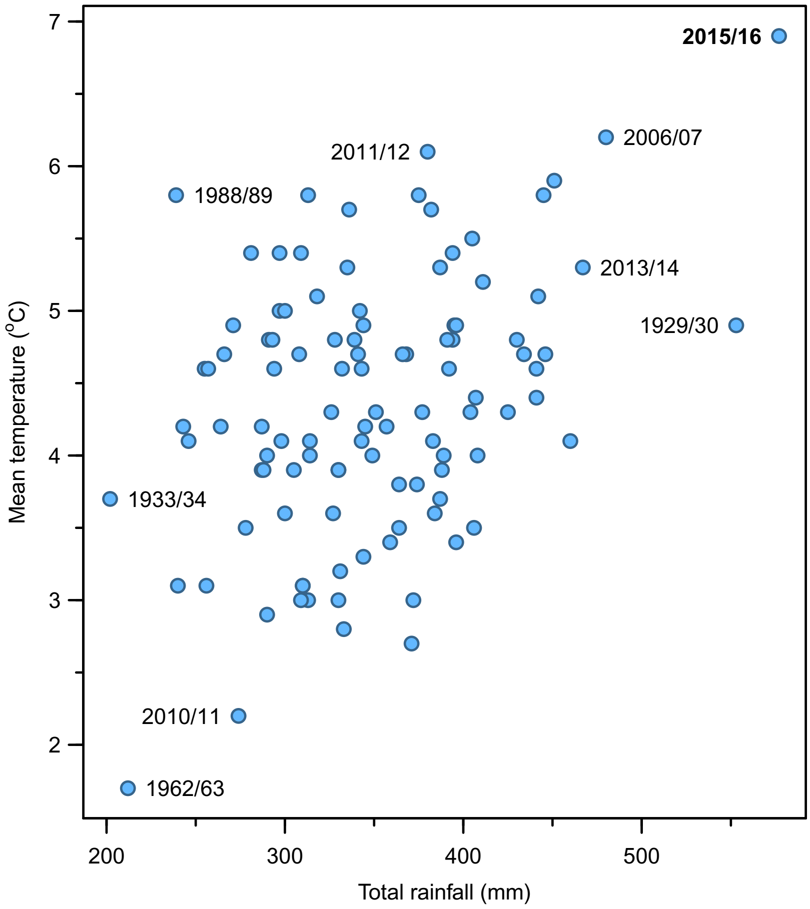


Figure 5 *November-January mean temperature (°C) and total rainfall (mm) for the UK from 1910.*

HYDROLOGY OF WINTER 2015/2016

Soil moisture deficits

In a normal year, soil moisture deficits[c] substantially moderate flood risk across much of the UK throughout the May-September period and their seasonal variation during the winter half-year is influential in determining the spatial extent and duration of flood episodes. In 2015, the dry early autumn was reflected in well above average soil moisture deficits which in a normal year would have delayed the onset in the seasonal recovery of river flows. The exceptional rainfall in the first fortnight of December rapidly eliminated the deficits across almost all regions apart from the English Lowlands. Subsequently, soils stayed close to saturation throughout the winter across most of the flood-affected regions (Figure 6) which were generally in regions where steep slopes and low-permeability rock strata imply an inherent vulnerability to intense rainfall.

River flows

Most extreme flow events in the UK are associated with individual storms across small or medium-sized catchments. The 21st century thus far has seen a number of very widespread flood episodes (see page 25) but none with the combination of severity, spatial extent and repetitive nature which marked the 2015/2016 flooding. The period of exceptional runoff was punctuated by four reasonably distinct episodes of extreme river flows and, in many areas, the flooding included fluvial and, locally, pluvial components.

Table 5 gives details of the peak flows and associated rankings for a selection of major rivers in the flood-affected regions and also provides estimated return periods. The credibility of a proportion of these new maxima is considerably enhanced by gaugings well in excess of 1,000m^{3}s^{-1} on, for example the Tyne (England, Plate 2) and the Tay; much to the credit of the hydrometric personnel involved. Return periods were estimated using the improved Flood Estimation Handbook (FEH) statistical methods[14] and the annual maxima used in the enhanced single-site analysis were sourced from the National River Flow Archive Peak Flows

[c] Computed using the Met Office Evaporation Calculation System (MORECS)[13].

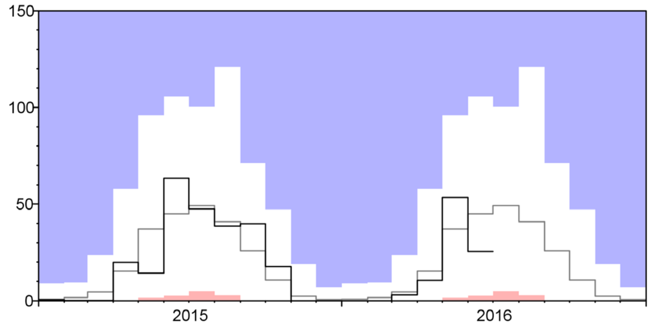


Figure 6 *Month-end soil moisture deficits (mm) for North West England.*

Note: *unless otherwise stated, blue envelopes represent period of record maxima to 2014, red envelopes represent period of record minima to 2014, and a grey trace may be used to indicate period of record mean to 2014.*

dataset version 4.1. This standard application did not allow for the use of additional local or historical flood information.

Considering the November to February flooding as a whole, it is likely that even more extreme peak flows than those reported here will have occurred in the headwaters of some of the featured catchments. However, gauging stations which combine long records with the capability to accurately measure flow rates substantially greater than bankfull are relatively rare in the areas subject to the most extreme rainfall (e.g. Cumbria, north Wales and the Cairngorms).

A timetable of the 2015/2016 flooding is given on pages 15-17. Figure 7 shows monthly mean river flow patterns for a selection of index catchments across the UK and Figure 8 shows daily flow patterns

Plate 2 *Acoustic Doppler Current Profiler gauging on 5th December during Storm Desmond on the Tyne at Bywell.*

Photo: Ian Downs, Environment Agency.

Table 5 *Peak flows and their associated return periods for selected catchments in the UK in December 2015 / January 2016 (based on current best estimates). Previous record figures are taken from NRFA Peak Flows dataset v4.1 and do not include pre-instrumental flow records.*

**Note that there is no upper bound to the return period range of >200 years and that some return periods may be substantially higher.*

***In Scotland, the pre-2016 records are only based on data up to 2005/2006, higher peak flows may have occurred since then.*

****Levels used to provide historical context due to uncertainty in the high flows. The Environment Agency confirmed the level is the highest on record.*

†No RP available as the improved FEH statistical method can not be applied to catchments with an $URBEXT_{2000}$ value greater than 0.03.

River name at gauging station	Catchment area (km^2)	Peak flow record start	New peak flow (m^3s^{-1})	Return Period of peak flow*	Date	Rank in month of occurrence	Pre-2016 maximum peak flow (m^3s^{-1})**	Month	Rank in any month	Pre-2016 maximum peak flow (m^3s^{-1})**	Month
Earn at Kinkell Bridge	591	1948	313.1	25-50	4th Dec 2015	1	237.2	Dec 1949	1	282.8	Feb 1950
Tweed at Norham	4390	1960	1361.0	10-25	5th Dec 2015	1	870.9	Dec 1985	6	1965.2	Jan 2005
Tyne at Bywell	2176	1956	1730.0	100-200	5th Dec 2015	1	1283.3	Dec 1964	1	1496.9	Oct 1967
South Tyne at Haydon Bridge	751	1959	915.0	50-100	5th Dec 2015	1	649.1	Dec 1991	2	929.8	Jan 2005
Mourne at Drumnabuoy House	1844	1982	925.5	25-50	5th Dec 2015	1	773.1	Dec 1991	2	1063.9	Oct 1987
Wear at Stanhope	172	1958	225.0	25-50	5th Dec 2015	1	167.8	Dec 2011	3	246.8	Jan 2005
Tees at Broken Scar	818	1956	614.0	10-25	5th Dec 2015	1	571.4	Dec 2011	6	646.3	Jan 1995
Lune at Caton	983	1968	1740.0	100-200	5th Dec 2015	1	882.1	Dec 1985	1	1395.2	Jan 1995
Spey at Boat of Garten	1268	1951	319.0	10-25	6th Dec 2015	2	392.8	Dec 1966	4	392.8	Dec 1966
Clyde at Daldowie	1903	1963	610.4	†	6th Dec 2015	3	1160.9	Dec 1994	7	1106.9	Dec 1994
Eden at Sheepmount	2287	1966	1680.0	>200	6th Dec 2015	1	936.0	Dec 1985	1	1516.4	Jan 2005
Dee at New Inn	54	1969	98.0	10-25	12th Dec 2015	1	80.1	Dec 1993	2	98.1	Nov 2009
Irwell at Adelphi Weir***	559	-	-	-	26th Dec 2015	1	-	-	1	-	-
Nidd at Hunsingore	484	1934	297.0	†	26th Dec 2015	1	252.0	Dec 1965	1	267.0	Sep 1946
Wharfe at Flint Mill Weir	759	1936	582.0	>200	26th Dec 2015	1	394.0	Dec 1936	1	417.3	Feb 1950
Ribble at Samlesbury	1145	1960	1110.0	†	26th Dec 2015	1	1010.0	Dec 1964	1	1040.0	Oct 1980
Calder at Mytholmroyd	172	1989	276.0	>200	26th Dec 2015	1	85.45	Dec 1991	1	191.9	Jun 2012
Conwy at Cwm Lanerch	345	1964	550.0	25-50	26th Dec 2015	1	492.2	Dec 2006	2	550.2	Nov 2009
Foss at Huntington	118	1988	40.0	†	27th Dec 2015	1	14.8	Dec 2012	1	17.0	Nov 2000
Aire at Armley	692	1961	350.0	†	27th Dec 2015	1	180.0	Dec 1978	1	235.3	Oct 2000
Dee at Woodend	1370	1929	1362.5	>200	30th Dec 2015	1	604.7	Dec 1932	1	1132.5	Jan 1937
Nith at Friars Carse	799	1957	752.2	10-25	30th Dec 2015	1	708.3	Dec 1982	2	908.4	Jan 1962
Cree at Newton Stewart	368	1963	476.2	150-250	30th Dec 2015	1	286.9	Dec 1991	1	375.0	Oct 2000
Tay at Ballathie	4587	1952	1811.0	25-50	4th Jan 2016	2	2267.9	Jan 1993	2	2267.9	Jan 1993
Ythan at Ellon	523	1983	183.3	>200	8th Jan 2016	1	84.9	Jan 1988	1	105.3	Feb 1996
Don at Parkhill	1273	1969	728.3	>200	8th Jan 2016	1	184.8	Jan 1970	1	454.3	Nov 2002

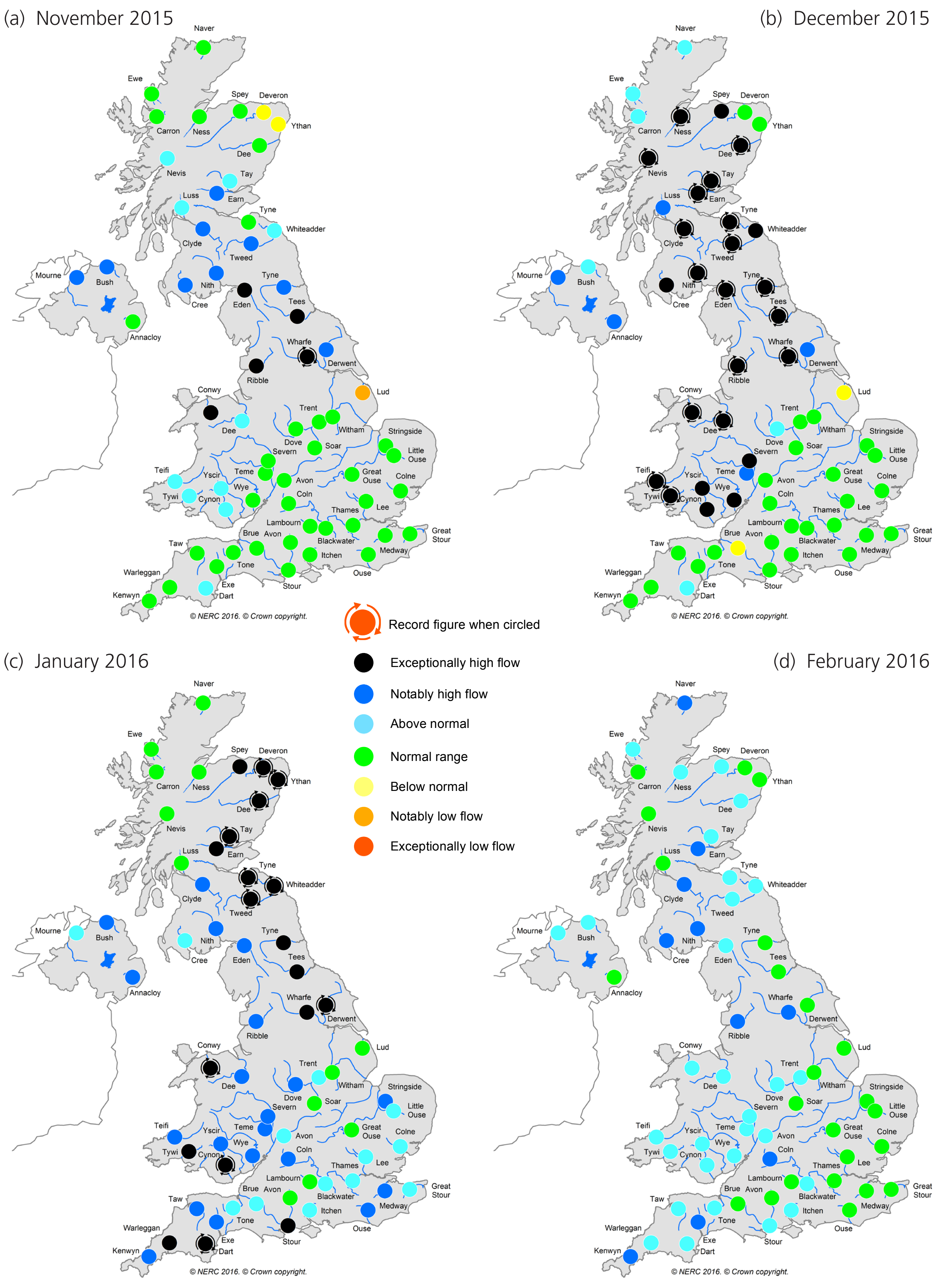


Figure 7 *Monthly mean river flows for November 2015 to February 2016. New period of record maxima are circled with arrows.*

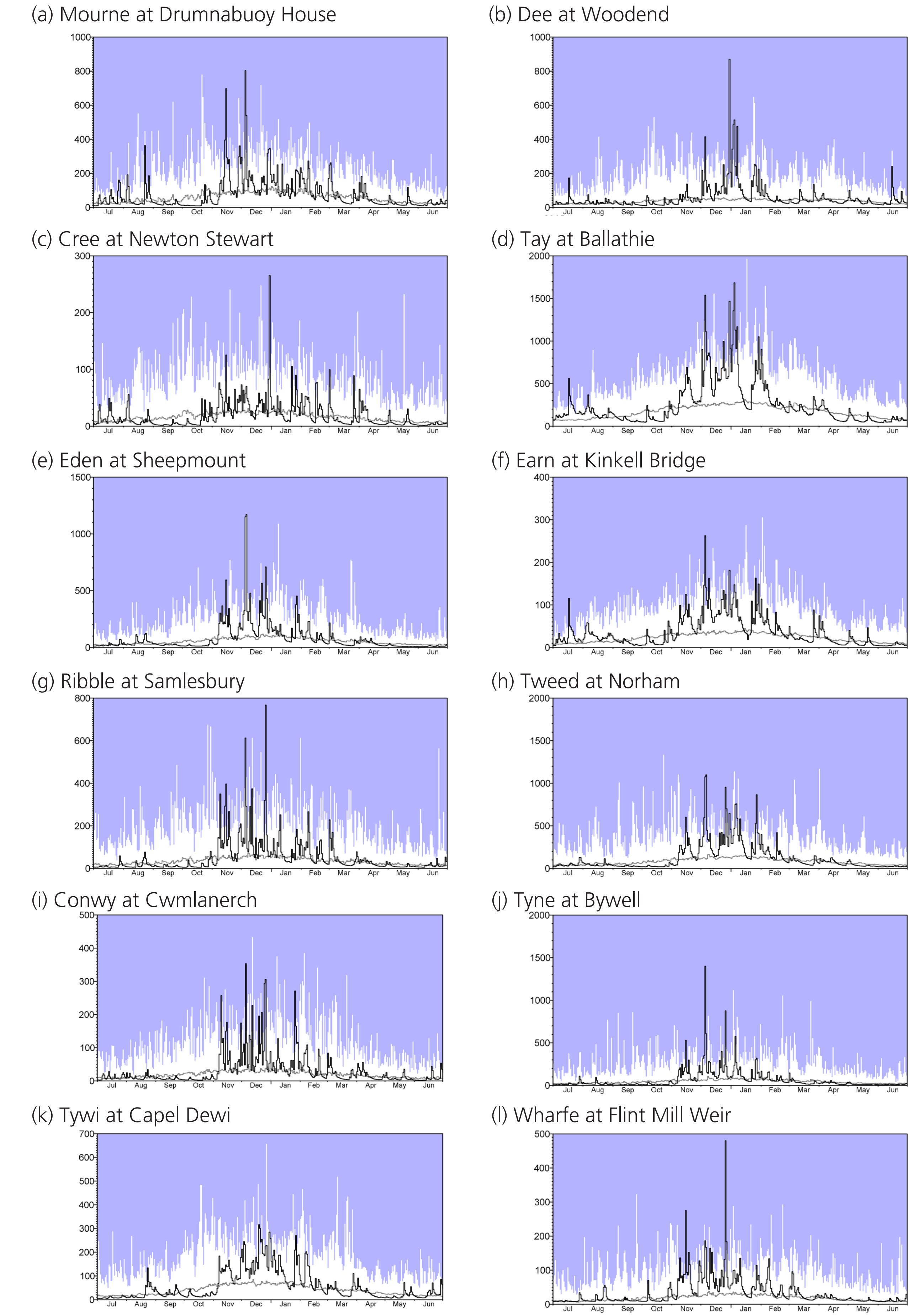


Figure 8 *Daily flow hydrographs (m^3s^{-1}) for July 2015 - June 2016 for selected gauging stations.*

for a representative set of gauging stations in the regions where, generally, the flooding was most severe.

Summer and autumn

Throughout the summer and early autumn of 2015 river flows across the UK remained generally well within the normal range but mostly below average. Estimated total outflows from Great Britain in early-November were less than half of the average for the time of year (Figure 9a). Steep recoveries in runoff rates began during the second week of the month in southern Scotland, northern England and north Wales, heralding a 14-week period during which exceptional peak flows and accumulated runoff totals were registered over much of northern and western Britain.

November

Protracted seasonal river flow recessions, with notably low flows registered in northern Scotland, were terminated in most impermeable catchments across the UK during early-November. Flood Alerts were common in south-west England by the 6th and the number of rivers in high spate rose rapidly. By the 9th, Flood Warnings were widespread and persistent across much of northern Britain and a number of major rivers draining from the Pennines registered new November maximum peak flows around mid-month (including the Ribble, Lune and Wharfe each with flow records of 50 years or more). More notably, on the 15th the Mourne in Northern Ireland recorded its third highest daily flow in a series from 1982. (Figure 8a) Flows generally declined during the third week but thereafter increased sharply and, for Great Britain as a whole, were extremely high around month-end (Figure 9a). Catchment runoff totals for the month remained within the normal range for most of southern Britain but exceeded twice the average across parts of northern England and north Wales; in West Yorkshire, the Wharfe recorded its highest November runoff in a series from 1955. Notably high runoff also typified much of southern Scotland and Northern Ireland (Figure 7a). With soil moisture deficits declining rapidly, the late-November spates implied that catchments across the UK remained very vulnerable to further rainfall.

December

Throughout most of December, river flows were exceptional with extreme flows widely recorded early and late in the month. In a zone from south-west Wales to north-east Scotland, previous maximum flows were exceeded, or closely approached, in a substantial proportion of gauged rivers. The winter 2015/2016 flooding began late in the first week during the passage of Storm Desmond. In Cumbria and Lancashire alone, 57 Severe Flood Warnings were issued and record peak flows were recorded on many rivers across northern England and

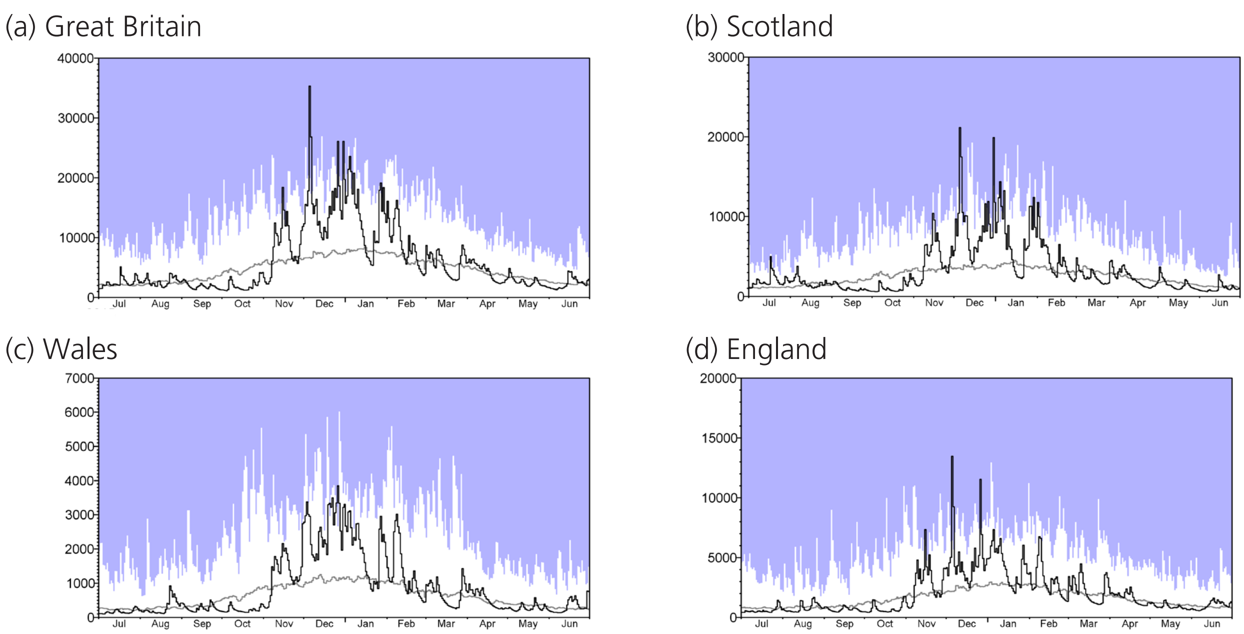


Figure 9 *Estimated daily outflows (m^3s^{-1}) from Great Britain, Scotland, Wales and England for the period July 2015 - June 2016.*

Scotland with extreme runoff in some areas (e.g. in north-west England where peak flows in more than half of the gauging station network exceeded their previous maxima).

In Northern Ireland, flows on the Mourne surpassed the mid-November peak and in northern England extreme flows were recorded on numerous rivers, for example, the Lune, Tyne and Eden. Each of these recorded maximum flows around 1,700m^3s^{-1}, exceeding the previous maximum for any river in England and Wales held on the National River Flow Archive. On the Tyne (England) the early-December peak was probably the highest since the great flood of 1771[15]. Reflecting the extreme rainfall, particularly exceptional peak flows were registered in most rivers draining the Lake District. On the Derwent and the Greta, for example, the peaks registered during the severe floods of November 2009 were exceeded by substantial margins and, in time series of around 40 years, the December 2015 maxima are clear outliers. Less direct, but still compelling, evidence of the magnitude of the December floods were the number of bridges destroyed or rendered dangerous during the events, including Pooley Bridge (Cumbria) built around 1764.

Following a brief respite mid-month, another outstandingly wet period generated further exceptional river flows and extensive floodplain inundations. By Boxing Day, Flood Warnings were widespread across Scotland and, for England and Wales, more than 200 Flood Warnings and 300 Flood Alerts were in operation. Runoff in parts of northern England was particularly extreme; the Calder, Ribble and Wharfe established new maximum peak flows (Table 5) and were among many Pennine rivers which exceeded or closely approached their previous maximum flows. Further bridge collapses were seen in northern Britain, including Tadcaster Bridge (North Yorkshire) built around 1700 (Plate 3). After another short respite, flows were again extreme following the passage of Storm Frank near the end of the month. In Scotland, flows on the Dee at Woodend peaked above the previous maximum (in a series from 1929) and a new maximum peak flow was recorded on the Cree (in a series from 1963; Table 5).

Plate 3 *Aerial view of the flood damaged A659 road bridge in Tadcaster, Yorkshire.*
Photo: Neil Mitchell, Shutterstock.

A large majority of index rivers in a zone from south-west Wales to north-east Scotland recorded new maximum runoff totals for December (Figure 7b) and, for most of these new any-month maxima were also established. The Tyne (England), Tees, Wharfe, Conwy and Eden each recorded more than three times the December average river flow (in record lengths of more than 45 years) and in many of the flood-affected regions the previous maxima were eclipsed by substantial margins. For example, the December mean flows for the Tweed in southern Scotland and Tyne in northern England were more than one and a half times the previous highest monthly mean flow on record (in series from 1962 and 1956, respectively). In some areas, the fluvial flooding during December (and subsequently) was exacerbated by a combination of sedimentation following the earlier floods, landslides and debris accumulations which, locally, reduced channel conveyance[16].

January

Entering 2016, soils remained saturated, river flows were very high across much of the country and most catchments remained vulnerable to even moderate additional rainfall. Parts of Scotland aside, the January flooding was less severe than in December but high spate conditions continued and significant floodplain inundations extended across many previously unaffected parts of southern Britain.

Intense downpours on the 2nd triggered many local flash floods in south-east England and, during the second week, flows approached or exceeded bankfull in many lowland rivers including the Thames and Great Ouse. To the west, particularly notable peak flows were recorded in Wales where many rivers remained close to, or above, bankfull early and late in the month with significant urban flooding (e.g. in Llanelli, south Wales, on the 3rd). Across much of northern Britain snow accumulations added to the flood risk and notable flows persisted throughout most of Scotland. Very high precipitation during the first ten days in eastern Scotland resulted in extreme peak flows on a number of rivers draining the Cairngorms. On the 6th, the Tay registered its seventh daily flow in excess of 1,000m^3s^{-1} in the space of eight weeks, an unprecedented cluster in a flow series from 1952 (Figure 8d). To the north, the Don at Parkhill recorded a peak river flow appreciably greater than the previous maximum in a series from 1969 (Table 5). Floodplain inundations were very extensive with many incidents of urban flooding (e.g. in Inverurie and Kintore). Colder and much drier conditions during the third week of the month provided a welcome respite, but Atlantic influences dominated once more over the 26th-28th accompanied by more heavy and persistent rainfall. Exceptional runoff rates with associated Flood Warnings and Alerts once again extended across much of the country.

New record January monthly flows were recorded in a substantial proportion of index catchments across eastern Scotland and in parts of Wales and Devon (Figure 7c). In Northern Ireland, the Annacloy recorded more than twice its average January runoff and the record November - January rainfall was directly reflected in a new maximum three-month runoff total for the Mourne catchment (in a series from 1981). The sustained high flows in many rivers across Northern Ireland produced an exceptional corresponding rise in the water level of Lough Neagh.

February

February rainfall for the UK was less than half that of December but the saturated nature of most catchments and, in a few areas, the sustained high outflows from springs and seepages ensured that flood risk remained high. The passage of Storms Henry and Imogen early in the month triggered widespread spate conditions with peak flows exceeding bankfull in some northern and western catchments. In Scotland, the Naver exceeded its previous maximum February daily flow on the 2nd (in a series from 1977) as did the Tone in south-west England on the 6th (in a series from 1961). Correspondingly, Flood Warnings and Alerts were once again extensive across northern and western Britain and extended to some central and eastern catchments (e.g. the Trent) during the second week. By the 8th, more than 50 Flood Warnings and 220 Flood Alerts were in operation across England and Wales and spate conditions persisted in many rivers across the English Lowlands – including the Thames where rising groundwater levels contributed a substantial baseflow component.

From mid-month however, recessions were sustained and generally steep and entering March flows in most index rivers were substantially below average for the time of year. For February as a whole catchment runoff totals were in the normal range across much of central and eastern England but still high in many western catchments (Figure 7d); estimated outflows from the UK were around 30% above the long-term average.

National and regional overview

The multiplicity of exceptional flow events over the November 2015 - February 2016 period is well demonstrated using the national and regional daily outflow series, which begins in 1961 and is based on measured flows around 80, mostly large, catchments throughout the UK[17]. Whilst, on occasions, substantial within-region variations in rainfall can result in flows in individual index catchments not being fully representative, the regional and national series constitute a homogeneous dataset based upon directly measured outflows from around 40% of the UK. This provides an objective framework within which to identify broad-scale runoff trends and make comparisons between major flood episodes.

New maximum outflows from Great Britain were recorded over a very wide range of durations (Table 6) – confirming the singularity of this episode over the last 55 years (the timespan for which sufficient hydrometric data exist to characterise flow patterns at the regional and national scales). Separate analyses confirm that the range extends well beyond 100 days, underlining the singular nature of the late autumn and early winter runoff at the national scale[d]. Maximum daily outflows

[d] The elevation and consequent wetness of northern and western Britain means that storms that cross these regions are likely to generate runoff which ranks highly in comparison with those following tracks across lowland areas of England.

Table 6 *Ranked Great Britain outflows (m^3s^{-1}) averaged over a range of non-overlapping n-day periods (since 1961). The date shown is the end date of the n-day period. Outflows during the period November 2015 - January 2016 are shown in bold.*

Rank	1-day		5-day		10-day		30-day		60-day		90-day	
	Date	Flow	Date	Flow	Date	Flow	Date	Flow	Date	Flow	Date	Flow
1	**05/12/2015**	**35302**	**07/12/2015**	**22169**	08/02/1990	19905	**14/01/2016**	**16449**	**30/01/2016**	**14824**	**11/02/2016**	**13593**
2	14/12/2006	26921	08/02/1990	22053	08/01/2016	19789	21/02/1990	15938	17/02/2014	14460	12/03/2014	12949
3	**06/12/2015**	**26815**	11/01/2005	21542	14/12/2000	18931	19/01/2014	15029	16/03/1990	13385	16/03/1990	11456
4	08/01/2005	26641	**07/01/2016**	**20798**	31/12/2012	18828	18/12/2006	14552	22/12/2000	13279	06/01/2001	11383
5	**26/12/2015**	**26078**	24/12/2012	20508	**10/12/2015**	**18435**	24/02/2014	14468	21/01/2007	12928	06/03/1995	11142
6	**30/12/2015**	**26072**	15/12/2006	20459	**30/12/2015**	**17935**	26/02/2002	13797	24/02/1995	11737	13/02/2007	10865
7	03/01/1982	25179	12/12/2000	19976	27/11/2009	17734	21/12/2000	13780	20/03/2002	11416	16/02/2013	10214
8	07/01/2005	25087	**03/01/2016**	**19946**	14/12/2006	17659	07/02/2008	13419	05/02/1994	10957	29/01/1993	9773
9	02/12/1992	25081	**30/12/2015**	**19668**	08/11/2000	17538	26/11/2000	13099	11/01/2013	10863	07/02/1983	9696
10	07/02/1990	23808	05/02/2002	19409	24/01/1993	17448	**13/12/2015**	**12994**	07/01/1987	10765	06/02/1975	9589

from Great Britain following Storm Desmond, the Boxing Day storm and Storm Frank all rank in the top six on record with the estimated outflows for 5th December 2015, exceeding the previous daily maximum by more than 30% (Figure 9a and Table 6); a clear outlier in the 55-year series of maximum daily outflows.

For England, the extreme flows in many northern catchments ensured that a new period of record daily maximum was established following Storm Desmond. In Scotland, where the limited monitoring of western outflows from the Highlands implies some uncertainty in the national runoff assessments, the outflows on both the 5th and the 30th December 2015 clearly exceeded previous daily maxima (Figure 9b). In Northern Ireland, where outflow patterns are dominated by flows on the Mourne and the lower Bann (which drains Lough Neagh), runoff on the 5th December 2015 was the second highest daily total – after 21st October 1987 – in a series from 1981.

Considering monthly timeframes, the December outflows from Great Britain eclipsed February 1990 as the maximum for any month in the national series. Over two months, the November - December runoff total was the highest for any pair of successive months in the 55-year national series with the exception of January - February 2014. For Scotland, the November 2015 - January 2016 runoff was around 20% higher than for any other three-month period. The corresponding runoff from Northern Ireland also established a new maximum for any three-month sequence. Outflows from Wales were less extreme but still exceptional with new runoff maxima established, albeit often by narrow margins, for timespans of one to six months.

Runoff through the winters of 2013/2014 and 2000/2001 also feature prominently in Table 6 whilst for the pre-1990 period, only the winter half-years of 1981/1982 and 1985/1986 were exceptional in relation to national runoff across the longer timespans. Average river flows from major catchments across Great Britain for the November 2015 to January 2016 period were exceptional; new period of record maxima were recorded in around a third of catchments for which data are submitted to the NHMP (Figure 10). Several of these catchments including the Tweed, Tyne (England), Conwy and Wharfe, approached or exceeded two and a half times the average flow for November - January. For Great Britain as a whole November - January outflows were the highest on record by a substantial margin (Figure 11), and were considerably greater than any three-month period in a series from 1961.

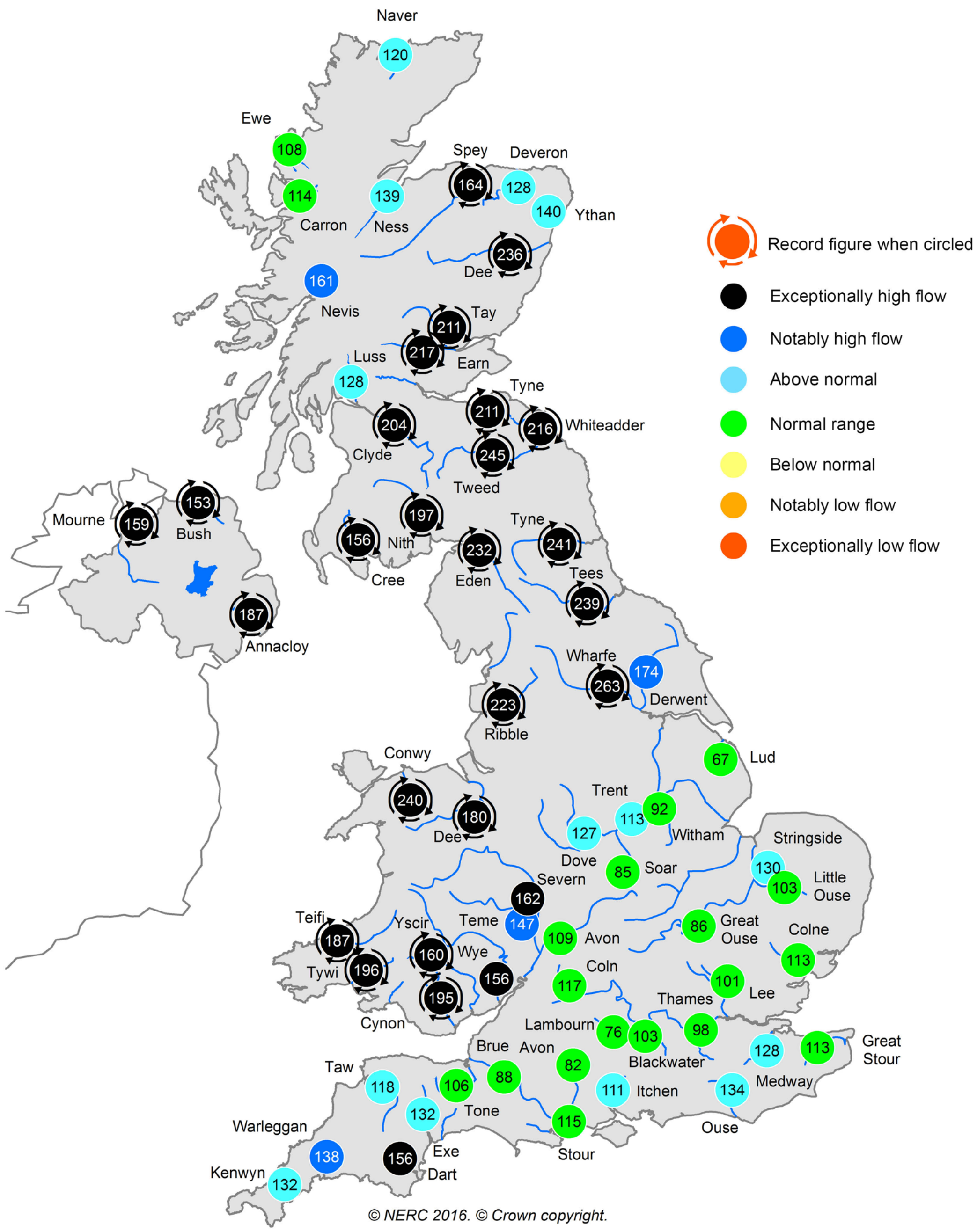


Figure 10 *Mean river flows for November 2015 to January 2016 expressed as a percentage of long-term average flows. New period of record maxima are circled with arrows.*

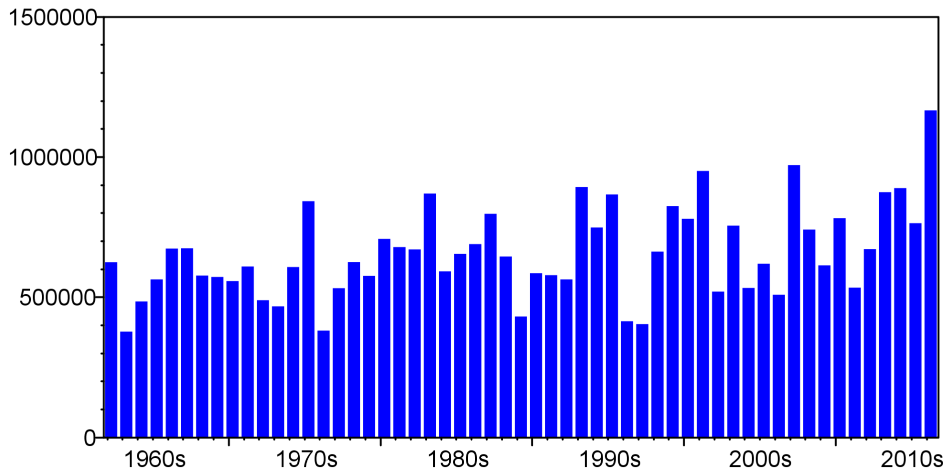


Figure 11 *November-January total outflows (m^3s^{-1}) from Great Britain.*

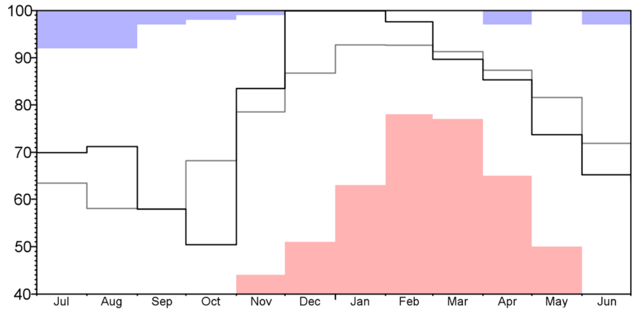
WATER RESOURCES OF WINTER 2015/2016

Reservoir stocks and flood mitigation

Across the UK, a wide range of hard and soft engineering options are used to moderate flood risk including retaining walls, controlled washland storage and, mostly small, flood retention reservoirs. In addition, large water supply and hydro-power reservoirs can play a role in flood mitigation depending in large part on the antecedent stocks. It is common practice in some areas for controlled releases to be made to provide additional storage for upstream flood runoff, normally through the winter half-year. This can be particularly useful where the reservoir commands a substantial proportion of the catchment above vulnerable urban centres. However, in 2015/2016 many of the at-risk communities were remote from catchment headwaters and the available reservoir storage represented only a small fraction of the runoff generated across the total catchment (see page 30).

Broadly speaking, reservoir stocks across most of the country were well within the normal range through the summer of 2015 but the normal seasonal recovery through the autumn was initially weak and stocks in most of the major reservoirs in the flood-affected regions were appreciably below average through the early autumn. In November stocks at Burnhope reservoir in north-east England increased by 44% during the week that Storm Abigail crossed the country[8] and storage in a group of major reservoirs in north-west England doubled between the end of October and the end of December (Figure 12a). For England and Wales the increase in reservoir stocks through November was the third highest monthly increase (for any month) in a series from 1995 and stocks continued to increase during December (Figure 12b). The remarkable late autumn and early winter replenishment ensured that spare reservoir capacity was generally limited by mid-November and, entering 2016, stocks in the majority of national index reservoirs (see Location Map) located away from the English Lowlands were near capacity. Healthy stocks continued to characterise these reservoirs until seasonal declines became established in mid-February.

(a) Northern Command Zone reservoir group



(b) England and Wales reservoirs

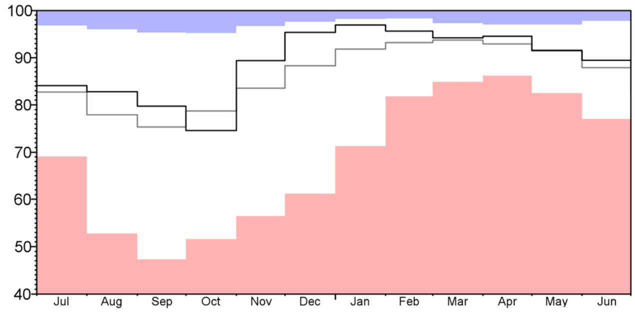


Figure 12 *Reservoir stocks (% of capacity) for July 2015 - June 2016.*

Groundwater

In 2015/2016, the most exceptional rainfall generally coincided with those parts of the country where aquifers are less extensive, and mostly have high storage capacities – making them much less susceptible to groundwater flooding. This contrasts notably with winter 2013/2014, where record rainfall across southern, central and eastern England resulted in unprecedented groundwater levels and sustained groundwater flooding, in the Chalk especially. Nonetheless, the extreme rainfall over many northern aquifer outcrop areas in late 2015 and early 2016 did trigger some outstanding increases in groundwater levels. Having been seasonally depressed in October, levels rose rapidly in many, but not all, northern index boreholes through the early winter. Exceptional levels were recorded in the Chalk at Killyglen (Figure 13a) and in the Permo-Triassic sandstones at Newbridge (Figure 13b). In the Chalk at Wetwang groundwater levels also rose very steeply through December leaving them close to their highest on record in early-January (Figure 13d). At the same time notably high levels in the Corallian Limestone in the Vale of Pickering triggered a sustained pumping programme to reduce groundwater

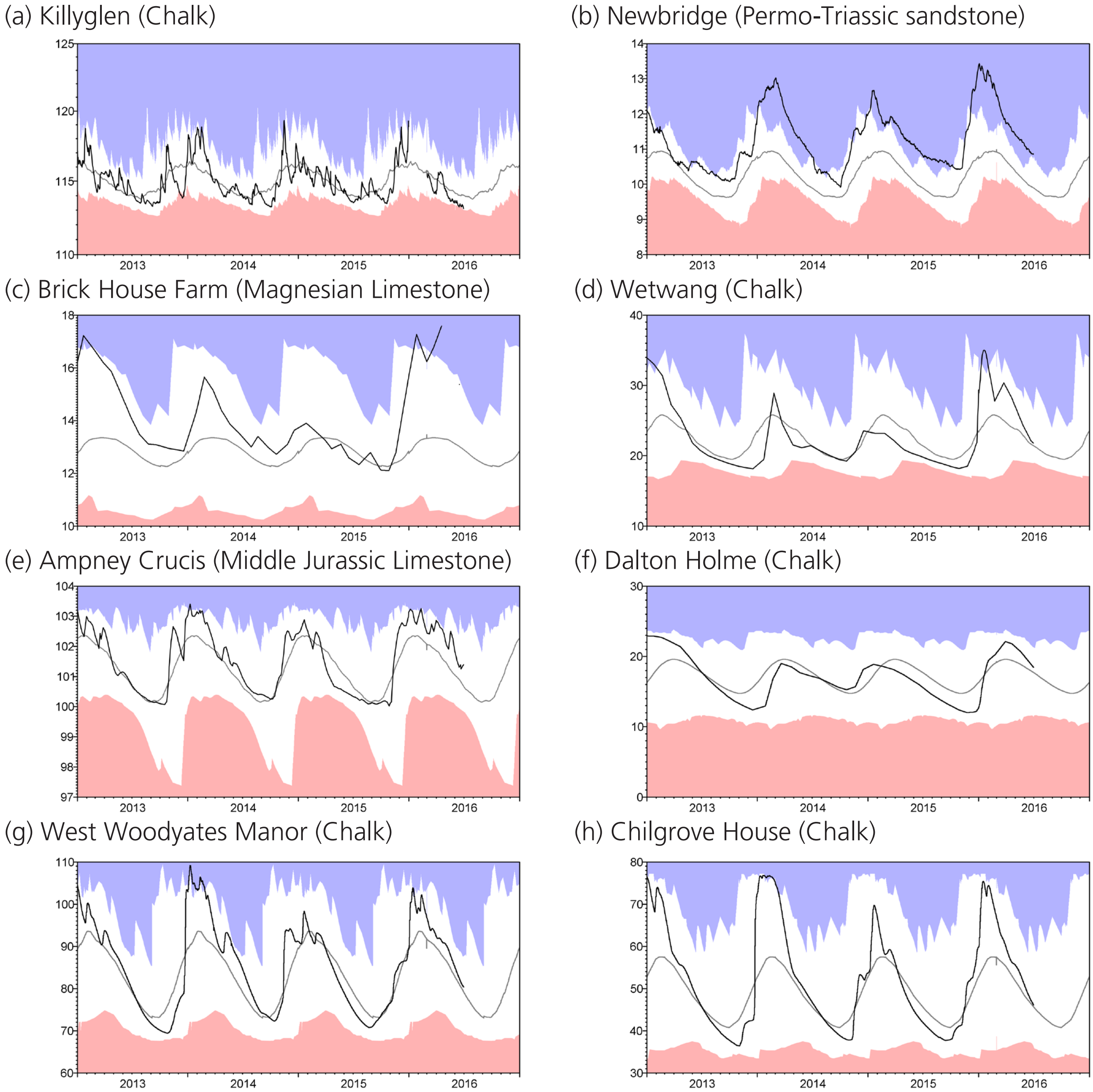


Figure 13 *Groundwater levels (in metres above Ordnance Datum) for selected boreholes for the period 2013-2016.*
Note: *Missing data at Killyglen due to storm damage.*

levels and prevent localised flooding in vulnerable communities (e.g. in Malton, North Yorkshire).

In contrast, across southern Britain the relatively modest rainfall in late 2015 left groundwater levels in most index boreholes within, or a little below, the normal seasonal range. The Jurassic limestones of the Cotswolds, which respond quickly to rainfall, were an exception (e.g. Ampney Crucis; Figure 13e). In January however, when rainfall approached twice the average across a few of the southernmost Chalk outcrops, the abundant recharge triggered a steep rise in groundwater levels, exceeding 15 metres at West Woodyates Manor (Figure 13g) and Chilgrove House (Figure 13h). As a consequence groundwater Flood Alerts were issued for some at-risk localities (e.g. in Dorset, Hampshire and West Sussex); some local surcharging of sewers and flooding of cellars was also reported. The limited infiltration from around mid-February rapidly moderated the flood risk but seasonally high groundwater outflows in many spring-fed streams contributed to a continuing fluvial flood risk in a number of rivers across the English Lowlands during the early spring.

IMPACTS OF THE FLOODING

The winter, defined by the successive flooding episodes, caused substantial impacts across northern and western Britain and Northern Ireland, with some communities being flooded multiple times. Around 16,000 properties were flooded in England in December alone, with more flooding in January. This is more than the 8,000 properties flooded in 2012[18] and 7,000 in 2013/2014[19], but substantially fewer than the 55,000 affected during the summer 2007 floods[1]. A comparison of flood events by impacts is problematic due to a number of factors, including the presence/absence of flood defences, antecedent conditions and area affected. It is little consolation to those who were flooded but worth noting that existing flood defences did protect over 20,000 properties during December. There was some overtopping of defences, but 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 caused considerable impacts on homes, businesses, industry, transport and agriculture.

The focus of the flooding during Storm Desmond was in northern England, particularly Cumbria, causing large scale flooding to an area which witnessed similar scenes in 2005 and 2009. The flood defence wall in Keswick, constructed following the 2009 flooding, was overtopped on the 5th (Plate 4), inundating 730 residential and business properties[20]. Carlisle was among the worst hit communities with 1,930 properties affected while in Kendal, 2,140 were flooded as the flood alleviation scheme built during the 1970s was overwhelmed[20]. The December storms also resulted in flood defences being overtopped in other communities in the north-west, including Cockermouth and Appleby, and in Lancaster thousands of properties lost power for several days when a large sub-station was flooded by the Lune. Further east, the Tyne burst its bank in several locations in Northumberland, people were evacuated from their homes and thousands of properties were without power[21]. In the Scottish Borders, Storm Desmond led to approximately 1,000 people being evacuated from their homes in Hawick as a result of the Teviot flooding. To the west, the Nith overflowed in Dumfries, flooding part of the town, and a major emergency was declared in Dumfries and Galloway

Plate 4 *Keswick's glass topped flood defences before (above) and during overtopping (below).*
Photo: Stuart Holmes.

as a result. Landslides and flooding closed some main and many minor roads in Scotland. Counties Down and Tyrone in Northern Ireland suffered road closures from fallen trees and emergency services were required to rescue flooded residents in Strabane as the Mourne burst its banks. On the Isle of Man, which had been affected by localised flash flooding on 3rd December, more extensive floodplain inundations occurred in the wake of Storm Desmond.

Substantial rainfall in mid-December brought more property evacuations, transport disruption and power outages (e.g. in north Wales). Over wide areas, extensive sediment movement in rivers and streams caused dramatic changes to channel morphology, impeding river flows as well as blanketing substantial areas of farmland, parks and other components of the floodplain with silt and coarser deposits. A substantial amount of rock/sediment was deposited in landslides following the extreme rainfall across the Helvellyn range. Large scale bank erosion and geomorphological change

Plate 5 *Bank erosion downstream of the North and South Tyne confluence.*

Photo: Richard Hill / Alex Mason, Environment Agency.

was seen in many catchments in northern and western Britain, for example on the Tyne (England) (Plate 5).

Persistent rainfall on already saturated ground up to and through the Christmas period kept many Flood Warnings in place and, by Boxing Day, there were over 200 Severe Flood Warnings across northern England, southern Scotland and parts of Wales, with accompanying exceptional river levels. In Cumbria, the village of Glenridding experienced flooding for the third time in just over a fortnight, with the persistent December rainfall creating enough flood water to lift and twist the Glenridding Pier road surface (Plate 6). The Boxing Day storm caused substantial damage in many catchments draining the Pennines: the Irwell flooded parts of Salford and, in West Yorkshire, many river levels exceeded bankfull[8], causing flooding in Whalley, Rochdale and Ribchester. In Calderdale, at least 2,000 homes in the valley were affected – for some the fourth major flood since 2000 – and an estimated 1,000 homes were flooded in Leeds as the Aire burst its banks. A mobile home park in Knaresborough (North Yorkshire) was evacuated. In York, 627 properties flooded; the number of properties affected would have been higher had the Foss Barrier not been raised[e].

The combined impacts of Storm Desmond and the Boxing Day storm on transport links were severe over large parts of the country, especially during the Christmas holiday period. Travel by both road and rail was disrupted, dividing and isolating

[e] For further details on the operation of the Foss barrier and the events of Boxing Day, see: https://www.gov.uk/government/publications/the-foss-barrier-reducing-the-risk-of-flooding/the-foss-barrier

Plate 6 *Road damage caused by flooding in Glenridding (Cumbria).*

Photo: Katie Muchan, CEH.

communities, particularly in Cumbria, Lancashire and West Yorkshire. The West Coast main line between Carlisle and Glasgow was closed following damage caused by Storm Desmond. Road travel in north-west England was also badly affected. The A591 between Grasmere and Keswick remained closed until the second week of May; whilst more than 30,000 tonnes of gravel was removed. Road diversions were also caused by the damage to or collapse of more than 100 bridges. Pooley Bridge (Cumbria) and Tadcaster Bridge (North Yorkshire), both 18th century structures, collapsed as a result of the winter flooding. A temporary replacement for Pooley Bridge was opened in March 2016 (Plate 7), and £3million was allocated by the Government for the rebuilding of Tadcaster Bridge. The Boxing Day storm closed the Conwy Valley Railway after washing away tonnes of ballast (the line did not re-open until the end of February) and, further north, flooding delayed TransPennine Express train services. The roads were also impacted when a sink hole opened up on the M62 in Greater Manchester on Boxing Day. Many roads and bridges were closed across Northern Ireland and northern Britain (North Yorkshire Police reportedly ran out of 'Road Closed' signs). The canal network was also affected with substantial impacts to the

Plate 7 *Temporary replacement for the collapsed Pooley Bridge, Cumbria.*
Photo: Katie Muchan, CEH.

Rochdale Canal, the Calder and Hebble Navigation and the Aire and Calder Navigation. During Storm Frank, the migration of the Dee eroded away part of the road between Ballater and Braemar causing a 120-mile diversion; a temporary road was opened in mid-January.

Throughout the winter flooding impacted communities across northern and western Britain, including some of the UK's major urban centres. Nearly 5,000 businesses across Northumberland, Cumbria, Lancashire, Yorkshire and Greater Manchester were affected by the storms, including the United Biscuits factory and Brunton Park football stadium in Carlisle and the Jorvik Viking Centre in York. There were also significant impacts on rural and agricultural communities. Low-lying farmland was inundated for extended periods and the December storms resulted in the loss of an estimated 2,000 sheep in Cumbria and many cattle were washed downstream in the swollen rivers over the duration of the flood episodes.

The duration of the high flows, and the repeated inundations in some catchments, caused particular problems for the civil authorities, with military assistance required to help the emergency services in some communities, restore transport links and assist in clear-up operations. The army was mobilised in Cumbria during Storm Desmond and across north-east England over the Christmas period, including in York (Plate 8).

First estimates for the insurance costs of Storm Desmond alone were some £520million but the final cost for damages to both homes and businesses for the winter of 2015/2016 is now likely to be >£1.3billion[22]. An initial tranche of £100million of government funding was released to assist stricken homes and businesses and to improve flood protection provision; a Farming Recovery Scheme was also launched to help restore damaged land.

Plate 8 *Chinook helicopter aiding flood response in York.*
Photo: Environment Agency.

MAJOR NATIONAL RUNOFF EPISODES

Episodes of broad-scale and protracted flooding in the UK are unusual but not particularly rare. Extensive flooding at the regional scale was experienced in 2013/2014[19], 2009[23], 2007[1], 2006, 2000/2001[24], 1998, 1995, 1990, 1986, 1982, 1974, and 1968. A preponderance of such events in the last 20 years is evident in Table 6 which demonstrates that, at a national scale, the two most outstanding runoff episodes since 1960 have occurred since 2012; only in 1989/1990 and 2006 have national daily outflows approached the exceptional *n*-day maxima registered in the second decade of the 21st century.

The winter of 2015/2016 was similar in a number of ways to 2013/2014, being notably stormy with a succession of deep low pressure systems bringing heavy and sustained rainfall across much of the UK. The winter of 2013/2014 remains the wettest winter on record for the UK and, for England & Wales the wettest in a series from 1766. Fluvial and tidal flooding was severe and throughout much of southern Britain groundwater flooding was an aggravating factor during most of the spring. Importantly however, the spatial and temporal distribution of the rainfall resulted in substantially less extreme flows than those experienced across northern Britain in 2015/2016.

Cumbria was also the focus of severe flooding in 2009[23], although many of the peak flow records set during this episode were broken in 2015/2016. The water year (October - September) of 2006/2007 was notable for both extreme summer flooding (e.g. in Yorkshire and the Midlands) and exceptional runoff through the winter, in December 2006 especially. However, apart from at the local scale (e.g. in Humberside), few peak flows approached those recorded during the 2015/2016 floods. In 2000/2001 the winter was not outstandingly wet but the preceding autumn was the wettest on record for the UK and notably high runoff was maintained throughout much of the October - December period[24]. With water-tables remaining exceptionally high groundwater flooding continued through into the late spring of 2001.

The sparse nature of the gauging station network prior to the 1960s, together with the different spatial footprints of major historical flood episodes, precludes any definitive quantification of national runoff during the extended flooding experienced in, for example, 1954, 1947, 1935, 1929/1930, 1914/1915, 1876/1877 and 1852. However, contemporary accounts provide valuable insights into the scale of the flooding and its impacts[25]. Such documentation confirms that the March 1947 event was particularly devastating – impacting communities across much of Britain, but most severely in the southern half of the country. Although the available evidence is incomplete it is likely that the 1947 flood was the most damaging fluvial event of the 20th century. It provided a major stimulation to the development of improved river management and flood alleviation strategies across the UK; a necessary initiative given the very substantial increase in urban and commercial development on floodplains over the following 70 years.

March 1947 witnessed extended and protracted flooding across England and Wales, following a combination of heavy frontal rainfall and a large snowmelt component (over still-frozen ground)[26]. The lack of gauging stations with records in 1947 implies that any estimate of the runoff at a national scale can only be a broad estimate. Nonetheless, it is very unlikely that the peak outflow from the UK or the accumulated runoff over a range of timespans, exceeded that registered in 2015/2016. It is also worth noting that the 1947 flood was, regionally, a far less significant event in north-west England than winter 2015/2016. Importantly however, flood protection was very rudimentary in 1947 and the hydraulic efficiency of most rivers was much lower than is currently the case; dredging, channel re-alignments and gravel extraction, for example, have increased conveyance substantially in many areas. Correspondingly, the lower runoff experienced in March 1947 could still be consistent with more extensive floodplain inundations than occurred in the recent flood episodes.

HYDROMETEOROLOGICAL TRENDS IN THE UK

The early years of the 21st century have seen exceptional variability in rainfall, runoff and groundwater recharge patterns. For the UK, average annual rainfall has been 9% greater over the 2000-2015 period compared to 1910-1999. A cluster of notably protracted high flow episodes have contributed to a 10% increase in average annual runoff for Great Britain in the 21st century thus far, relative to the previous 40 years. The increase is disproportionately concentrated in the winter months: October-March runoff is around 15% greater over the post-1999 period.

Correspondingly, attention has focused on the need to identify, quantify and interpret hydrological trends across the UK, those relating to flood frequency and magnitude in particular. The degree of climatic variability experienced in the UK and, to a lesser degree, the influence of river and catchment management practices on river flow patterns, implies that identifying resilient long-term hydrological trends remains a considerable scientific challenge. Fortunately, the UK's rich legacy of meteorological data extending back, locally, to the 16th century provides direct observational evidence of changes in temperature and rainfall. Generally, river flow and groundwater level records are substantially shorter but there is a large amount of hydrometric data for the period since the 1960s, which has seen the most compelling warming trend. The challenge is how best to interpret the associated hydrological changes.

Average temperatures across the UK have increased by more than 1°C over the last 100 years with a particularly steep rise since the early 1960s. This is reflected in the rise of sea levels[27] and a corresponding increase in the risk of tidal flooding. However, the relationship between rising temperatures and precipitation patterns (and consequent flood risk) across the UK is complex. For example many areas have seen a decline in snowfall as a proportion of total precipitation as temperatures have risen[28]. Nonetheless, an increase in snow cover over the western Cairngorms occurred over the 2002-2013 period[29] and increasing melt rates in a warming world may also be an exacerbating factor in relation to flood risk, albeit a temporary one. Generally in this context though, warmer winters should prove beneficial with a lower frequency of the snowmelt-aggravated flooding.

Rainfall intensity and duration are the major contributory factors to flood risk in the UK and a number of studies have identified a tendency for a higher proportion of rainfall to fall in more intense events[30,31,32]. There is considerable regional variability in these changes but a feature of most studies is that the greatest increases are in northern and western regions and, particularly, in upland catchments during the winter period. The flooding in 2015/2016 is consistent with this tendency but, by their nature, outstanding rainfall episodes extending over tens of thousands of square kilometres are infrequent.

Considerable effort has been invested in characterisation of trends in fluvial flooding. In the 1990s, a national trend detection study, capitalising on floods data assembled as part of the Flood Studies Report and Flood Estimation Handbook research programmes and embracing more than 800 flood time series[33], found little evidence of any increase in flood magnitude or frequency consistent with anthropogenic climate change. However, the importance of interannual and interdecadal variability in long-term hydrometric records in the UK became firmly established; an observation that has been endorsed repeatedly by many subsequent studies[34]. One of the issues with the key finding of a lack of significant trends was that the studies primarily adopted a UK-wide focus and were aggregated across all sites, including catchments with very different characteristics and incorporating rivers affected by a range of anthropogenic disturbances (e.g. urbanisation, reservoir development etc.) which could modify any climate-driven flood signals. The identification of a UK Benchmark Network of gauging stations[35] allowed hydrological trend detection studies to focus on well-monitored catchments, with gauging stations capable of measuring flood flows effectively[36,37].

In 2015, a comprehensive literature review confirmed that the results of the earlier trend analyses capitalising on the Benchmark Network chime with a multitude of contemporary, but generally more local scale, studies[38]. Although a tendency for high – as opposed to extreme – flows to occur with an increasing frequency can be recognised, a general consensus points to very limited compelling evidence for long-term trends in flood magnitude in the UK. The majority of statistically significant trends were found for periods from the 1960s up to the mid-2000s, predominantly in northern and western upland areas, and in the winter half-year. However, published studies have not yet incorporated the most recent flood events; for example, the most recently published Benchmark trend studies use river flow time series ending in 2008. Up-to-date analyses will be published in the near future as part of an ongoing review of the Benchmark Network. An early outcome of these analyses (Figure 14) confirms the tendencies seen in past studies, demonstrating that Q_5 flows (the flow exceeded 5% of the time) in many western benchmark catchments have increased from the 1950s up to 2013. For selected catchments, daily flow data including the winter 2015/2016 has been incorporated to provide an up-to-date perspective. In these cases also, increases in peak flow magnitude can be seen, particularly in the more 'westerly' influenced catchments (the Tay and the Eden) where increases are significant (Figure 15).

Importantly, interpreting any emerging trends can be challenging. Whilst increases in winter rainfall and runoff are entirely consistent with future climate projections, the increases are strongly associated with variations in the North Atlantic Oscillation (NAO), the leading mode of atmospheric variability in Northern Europe. Attribution of runoff changes to anthropogenic climate change is hampered by the relatively short records and the association with the NAO, which may itself be affected by anthropogenic warming but also incorporates much internally driven natural variability.

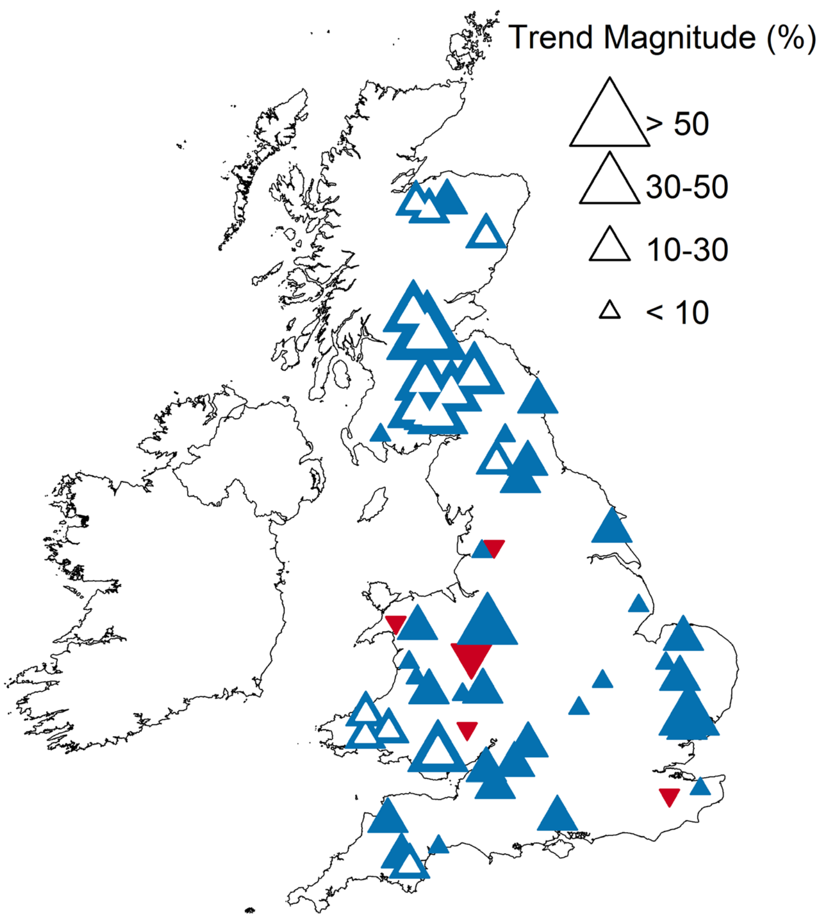


Figure 14 *Trends in Q_5 (derived from daily flows) at the UK Benchmark stations with records covering the period 1954-2013. Blue/red triangles represent an increasing/decreasing trend and the size of the triangles represent the magnitude of the trend (%). Hollow triangles show a statistically significant increase/decrease at the 5% level using the Mann-Kendall test.*

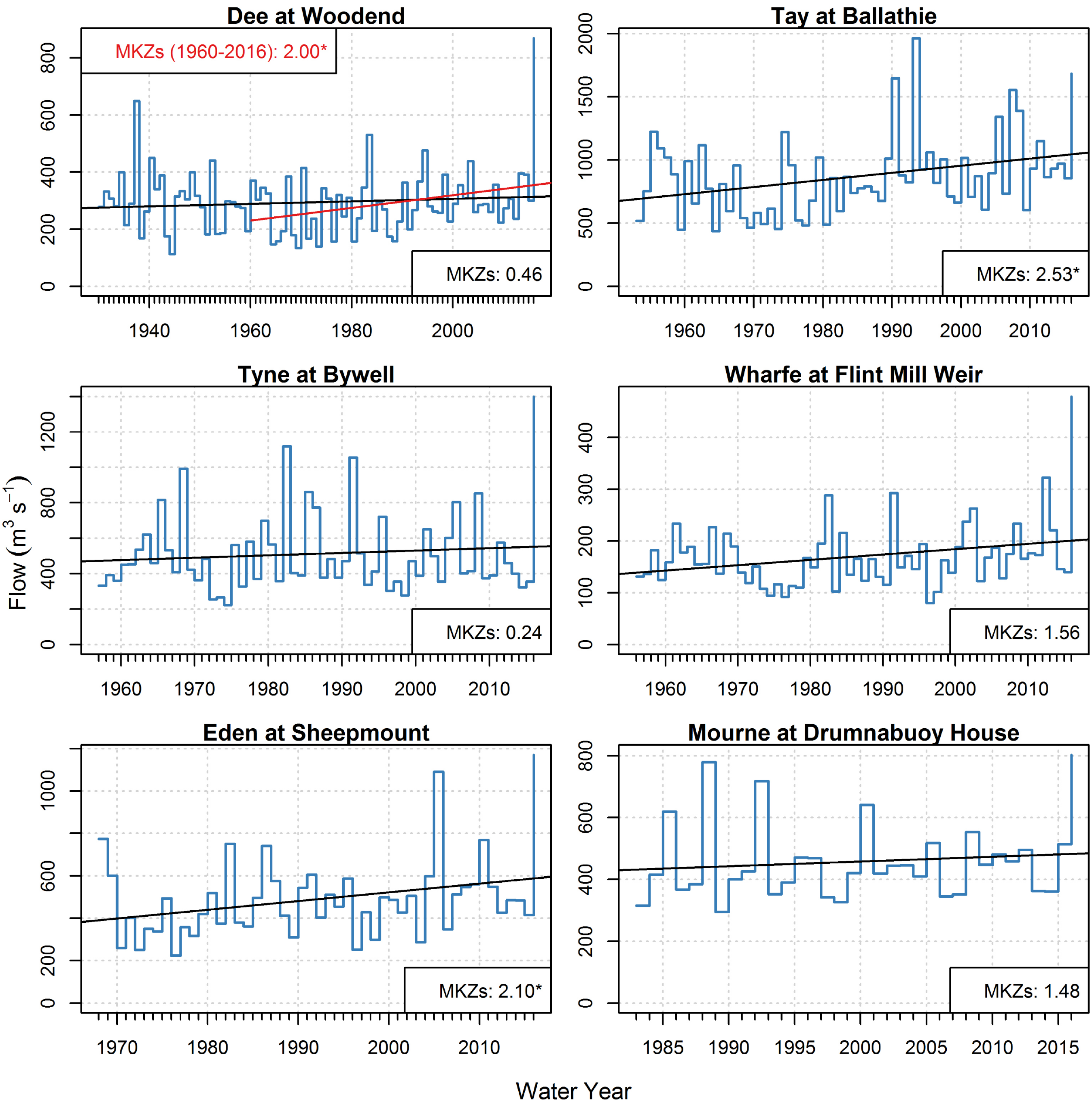


Figure 15 *Trends in water year (October - September) maximum daily flows. Trend lines (solid black) are given by linear regression and evidence of trend by the standardised Mann-Kendall statistic (MKZs). Significant trends are marked with an asterisk (*). For comparison, the trend over water years 1960-2016 is also estimated for the Dee at Woodend (solid red line).*

In relation to river flow patterns it is important to reiterate that prior to the 1960s the UK hydrometric network was very sparse. Rapid growth ensued through the 1960s and 1970s but crucially, these decades were characterised by notably low winter rainfall; the 1957-1976 period registered the lowest 20-year winter half-year rainfall for the UK in a series from 1910 (Figure 16). The associated modest runoff during the decades when most gauging stations were commissioned may imply that any apparent tendency towards a subsequent increase in river flows and a possible associated increase in flood risk is unsurprising. This is illustrated by the example in Figure 15, which shows the difference between a trend in water year maximum daily flows from 1960-2016, relative to the full period of record (from 1929), for the Scottish Dee. Such issues, together with a need for a better understanding of the synoptic driving mechanisms, complicate the identification of resilient trends relating to flood risk.

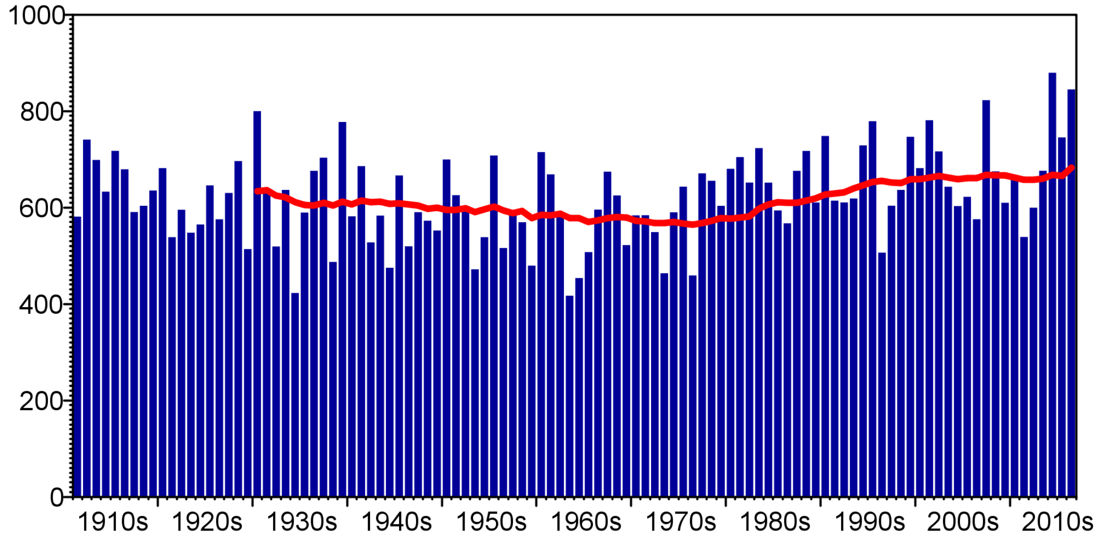


Figure 16 *Winter half-year (October - March) rainfall (mm) for the UK with a 20-year running mean (red line).*

Given the comparative brevity of UK river flow records, in the face of high inherent natural variability, the attribution of any observed trends to anthropogenic warming remains a significant challenge using observed records alone. There is a growing literature on '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 the event was made more likely due to human influence on the climate[39,40]. A similar study for the winter 2013/2014 floods[41] 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 only a week after the December 2015 flooding, claiming that the Storm Desmond rainfall was made 40% more likely as a result of anthropogenic warming[31]. However, this was based on very preliminary data; future studies will no doubt be published building on this approach.

Whilst the inherent variability in UK runoff patterns is reflected in the modest statistical significance in most trends in high flows, such trends are strategically important and it is vital that the homogeneity in UK hydrometeorological time series is maximised. Changes in monitoring networks and advances in sensing and recording technologies, together with the mechanisms used to aggregate point measurements into areal averages, can all impact significantly on time series homogeneity[42,43,44]. This is particularly true of flood datasets where, for example, the widespread deployment of acoustic doppler measuring techniques has greatly reduced the uncertainties associated with extreme flow assessments. However, the improved accuracy that the doppler technique provides may raise questions about the accuracy of the peak flows ascribed to earlier major flood events in the time series. Correspondingly, the highest standards of data and metadata management will be needed to ensure that changes in flood magnitude and frequency through the 21st century can be effectively indexed[45].

DISCUSSION

The outstanding runoff through the winter of 2015/2016 and the resulting repetitive flood episodes in many regions of the UK raised important questions about the adequacy of existing flood alleviation and management strategies. In response to the wide range and severity of the flood impacts, the Government instigated a National Flood Resilience Review to ensure that the country can deal more effectively with extreme weather events. The review examined forecasting and modelling capabilities, the resilience of key infrastructure and the way decisions are made about flood expenditure[46].

The sheer volume and intensity of the rainfall during the late autumn and winter of 2015/2016 was the primary cause of the exceptional peak flows and sustained high runoff. However, in circumstances where a modest reduction in extreme flows would have had obvious benefits, flood mitigation options including the influence of catchment land use, river engineering, land drainage practices and the creation of catchment storage structures will, once again, need to be the focus of research effort.

The vulnerability of many communities and commercial activities to flood-related damage was heavily underlined during the protracted flood episodes. In addition, the resilience of the UK's transport infrastructure was severely tested. In part, this is a reflection of the fact that many major road and rail links capitalise on the generally gentle topography afforded by floodplains. The associated vulnerability was clearly exposed during the 1947 flood when, in its aftermath, many road and rail embankments were raised to make some arterial routes more flood-resilient. Work on raising the tracks of part of the main rail link south from the Midlands through Oxford, following the 2013/2014 flooding, is likely to foreshadow substantial further investment to moderate flood risk across the UK transport network.

Hydrology at the large catchment scale is an extremely complex mixture of natural and man-made water processes, pathways and storages. In assessing the effectiveness of potential flood mitigation measures it is essential to consider the scale and magnitude of the flooding. Mechanisms that would substantially moderate the impact of a flood expected once every five years (on average) may have little or no impact faced with record rainfall over a large catchment where the resulting peak flows have return periods in excess of 100 years.

In addition, the repetitive nature of the exceptional runoff episodes of the type experienced through the late autumn and winter of 2015/2016 implies that the potential for floodwater storage (at scales from informal log dams to major reservoirs) would have been limited in many areas. Some reservoirs (e.g. in Cumbria) command a substantial proportion of the catchment above urban centres and, clearly, have potential to moderate flood peaks. More typically however the reservoired fraction above many urban centres is small relative to the overall catchment size. Thus, although tactical drawdowns of storage clearly has potential to moderate flood risk, that potential is limited in situations like the winter of 2015/2016 when most impoundments were full by early-December and the opportunities for natural drawdown in the intervals between the succeeding major runoff episodes were restricted in many areas.

In 2015/2016, most flood defences worked effectively (although as noted, some were overtopped due to the severity of the flooding) and the importance of natural or controlled floodplain storage was underlined. Whilst demountable flood barriers were not always deployed in sufficient time, their general utility was well demonstrated in some catchments (e.g. along the Severn). Certainly, flood defences substantially reduced the scale of the inundations, and the overall number of properties flooded may be considered relatively moderate in the context of the record rainfall and the runoff experienced through the winter of 2015/2016. Flood resilience has also benefitted from the notable improvement in weather forecasts, particularly in the three to five day timeframes, together with the range of flood warning capabilities operating across the UK and the ability to map vulnerable localities with greater precision, has contributed to an enhanced level of preparedness.

Natural geomorphological changes and many flood mitigation options – for example dredging, gravel extraction and channel re-alignments – can have complex consequences for flood risk[47,48]. Any intervention that diminishes the potential for local floodplain storage is likely to increase downstream flows. Thus, whilst providing short-term and local palliative improvements, resilient solutions need to ensure that what works locally does not significantly exacerbate downstream flood risk. Any strategy to moderate flood risk must incorporate measures to restrict development on vulnerable floodplains but, in recognition of pressures on the housing stock a new national scheme to help provide better access to affordable flood insurance, FloodRe, was introduced in April 2016[49]. The scheme is restricted to houses built before 2009 as a disincentive for building companies to skimp on flood alleviation infrastructure.

The 2015/2016 flooding stimulated considerable discussion of more natural-based approaches to flood mitigation (widely referred to as natural flood management) within the wider context of rewilding. There are many such initiatives that will work to some extent in some locations[48] but it is unlikely that any one of them will work to the same extent everywhere, or will provide a panacea for protecting all communities and all sites against flooding. Some proposed measures, small log dams for example, have important ancillary benefits in addition to water storage such as holding back sediment load and providing improved habitats for wildlife. Thus they can have considerable ecological value as well as contributing to flood mitigation at a local scale. But, as the scale of the flooding increases, they generally become less effective since, like dams and other flood retention options, they only work until the available capacity is exhausted. Correspondingly, in extreme floods their moderating impact, though locally important, is likely to be small.

There is currently limited documented scientific evidence that different upland management practices would have significantly moderated the winter 2015/2016 flooding. Measures including upstream land management and informal (leaky) dams installed in moorland and forest drains were found to moderate flows from the North York Moors during December 2015[50] but, importantly, would have limited impact on the flows generated by the extreme rainfall experienced in the worst-affected catchments in Cumbria or the Pennines. In relation to land use patterns, long-term research undertaken at Plynlimon[51] in central Wales demonstrates that the contrast in response between upland forested and grass catchments, while discernible in modest floods, is insignificant during extreme rainfall events[52] (Figure 17). That is not to say that planting trees or creating a more varied mosaic of upland land use does not have the potential to reduce peak flows or to usefully stagger the arrival of tributary peaks into main rivers, thereby reducing the degree of floodplain inundation associated with small to moderate flood events. Combined with rewilding initiatives such land use changes may well have significant additional benefits in terms of landscape enhancement and ecological diversity.

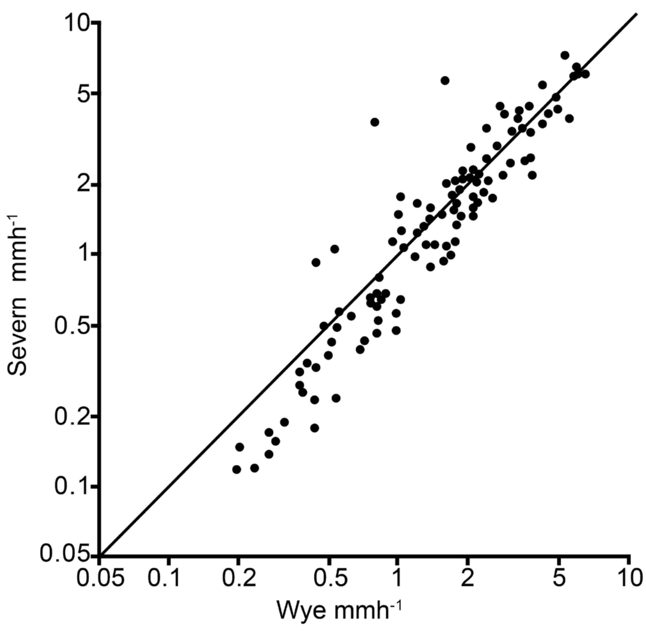


Figure 17 *Comparison of the peak runoff rates on the Wye (deforested) and Severn (70% forested) catchments at Plynlimon[52]. Flows are expressed as hourly runoff rates.*

CONCLUDING REMARKS

Many new rainfall records were established across the UK within the November 2015 - February 2016 timeframe and the extent, severity and duration of the resulting flooding has few, if any, close modern parallels. The exceptional flows, together with those experienced in southern Britain over the December 2013 - March 2014 period, has extended the range of recorded runoff variability in many regions and underlined the UK's continuing vulnerability to extreme rainfall episodes.

The flooding attracted much public, media and political attention, and considerable speculation relating to the effectiveness of existing flood management strategies. The possibility that similar flood episodes may occur with a greater frequency in the future underpins the need for more detailed catchment-based studies to understand more fully the exceptional hydrological responses in the most severely impacted regions through the winter of 2015/2016. Such studies are needed to provide a richer information base to underpin improved engineering design procedures and more resilient flood management strategies.

There is much still to be learnt about the potential for natural flood management techniques and how they can best be utilised alongside more traditional approaches. Correspondingly, there is a pressing need to systematically review all the evidence to determine what works best in any particular catchment. Additionally, it is important to build on the extensive educational material currently available (e.g. the Government's 'Floods Destroy - be prepared' campaign) to better inform the population of the risk of flooding and the actions, including more effective flood-proofing of housing stock and commercial premises, that can be taken to reduce those risks.

The moderate increase in runoff in the 21st century relative to the previous 40 years, possibly linked to climate change, demonstrates the inherent variability of UK river flows. The fact that the earlier 'flood poor' period dominates the hydrometric time series for the majority of gauging stations calls into question the homogeneity of the data. Correspondingly, there is a particular need to establish whether the increased runoff in the 21st century is part of a resilient long-term trend. This requires a more penetrating understanding of the mechanisms driving flood variability and a continuing need to devote sufficient resources to the accurate measurement of flood flows across the UK.

Acknowledgements

The credibility of any examination of a major hydrological episode is heavily dependent on the availability and quality of hydrometeorological data. The assistance of all involved in the acquisition, processing, validation and archiving of the data utilised in this report is gratefully acknowledged. In particular, extra information and advice was provided by Richard Hill, David Lindsay, Peter Spencer, Tony Andryszewski and Richard Davis (Environment Agency), and Una Thom and Nigel Goody (Scottish Environment Protection Agency).

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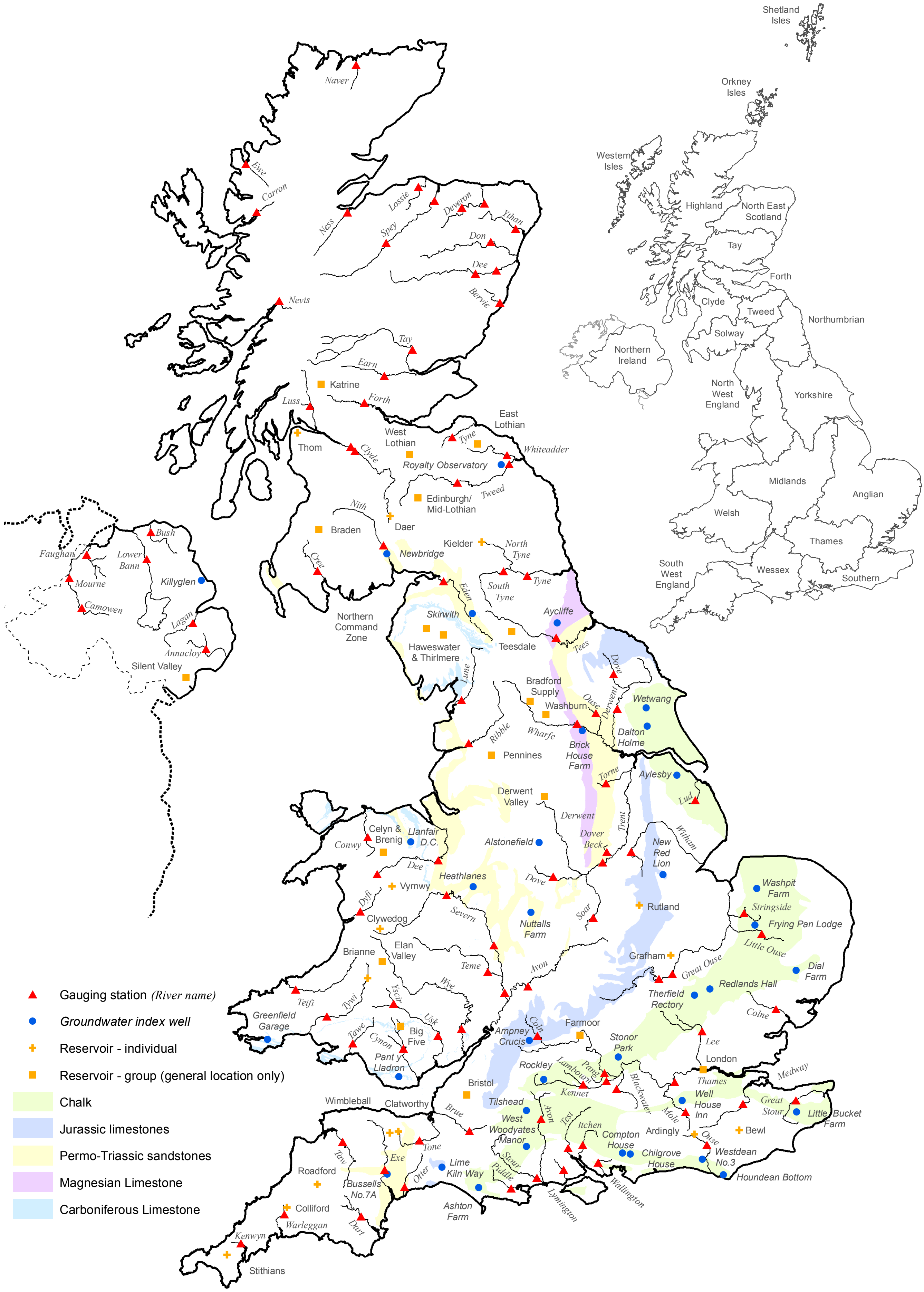
Location map



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