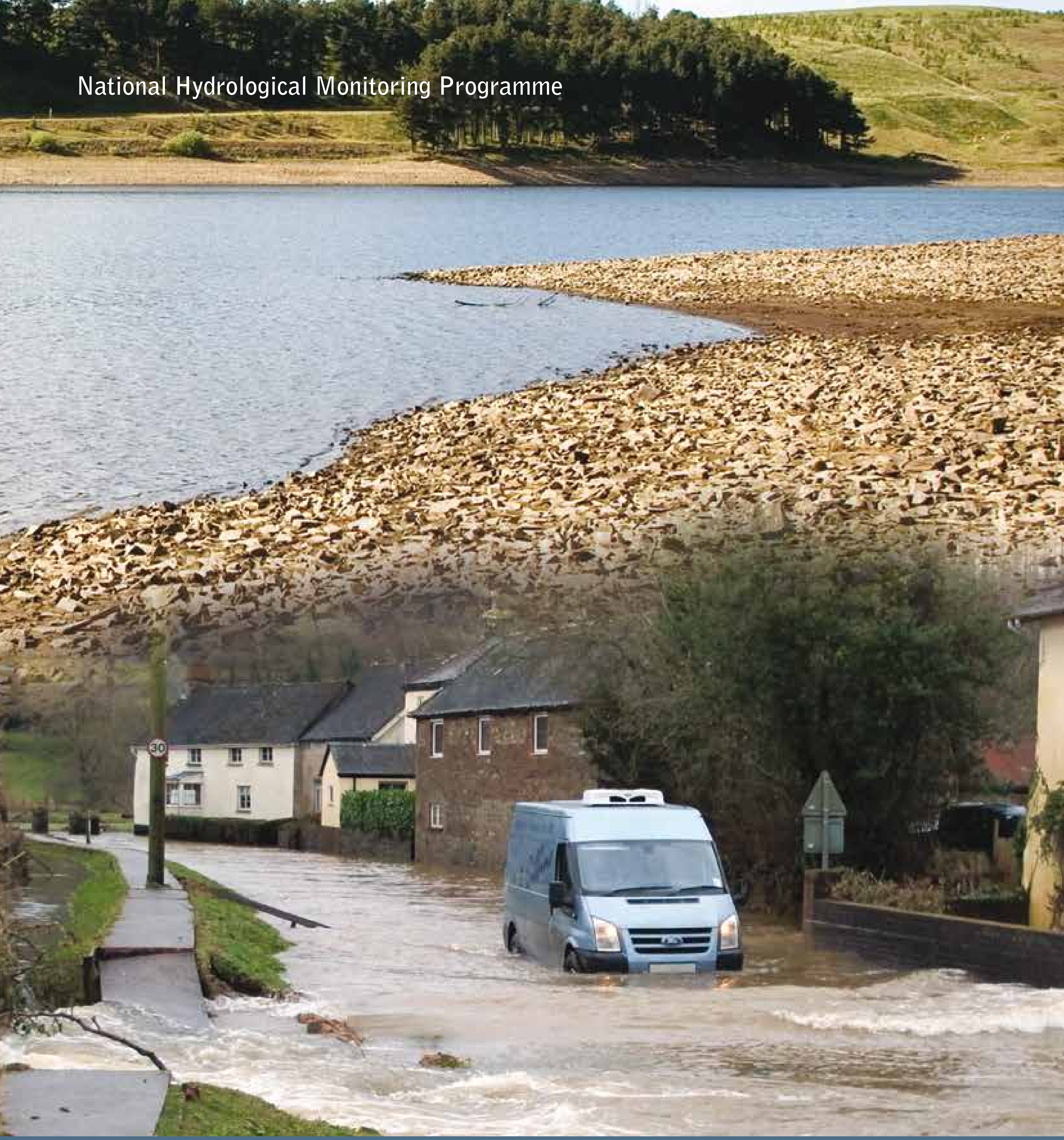
National Hydrological Monitoring Programme



The 2010-12 drought and subsequent extensive flooding

- a remarkable hydrological transformation

by Terry Marsh, Simon Parry, Mike Kendon & Jamie Hannaford

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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THE 2010-12 DROUGHT AND SUBSEQUENT EXTENSIVE FLOODING

– A REMARKABLE HYDROLOGICAL TRANSFORMATION

The work for this report was carried out by scientists from the Centre for Ecology & Hydrology (CEH), the UK's centre of excellence for research in land and freshwater environmental sciences in partnership with the Met Office; technical guidance was provided by the British Geological Survey (BGS), the UK's premier centre for earth science information and expertise. Funding was provided by the Natural Environment Research Council.

The report was compiled with the active cooperation of 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, in Northern Ireland, the Rivers Agency. These organisations provided the great majority of the required river flow and groundwater level data. The Met Office provided almost all of the rainfall and climatological information featured in the report. The reservoir stocks information derive from 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, is gratefully acknowledged.

The National Hydrological Monitoring Programme

This report is an output from the National Hydrological Monitoring Programme (NHMP) which is operated jointly by the CEH and BGS. The NHMP was set up in 1988 to document hydrological and water resources variability across the UK and to identify and quantify trends in runoff and aquifer recharge patterns. As part of this programme monthly Hydrological Summaries for the UK are routinely published.

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://www.ceh.ac.uk/data/nrfa/nhmp/nhmp.html.

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INTRODUCTION

Across most of the UK, the 2010-12 period was remarkable in climatic terms with exceptional departures from normal rainfall, runoff and aquifer recharge patterns. Generalising broadly, drought conditions developed through 2010, intensified during 2011 and were severe across much of England & Wales by the early spring of 2012. Record late spring and summer rainfall then triggered a hydrological transformation that has no close modern parallel. Seasonally extreme river flows were common through the summer, heralding further extensive flooding during the autumn and, particularly, the early winter when record runoff at the national scale provided a culmination to the wettest nine-month sequence for England & Wales in an instrumental record beginning in 1766.

This report provides comprehensive documentation and hydrometeorological appraisals of a three-year period which incorporated a number of important regional drought episodes as well as the outstanding runoff and recharge patterns which characterised most of 2012. An examination of the wide range of impacts of the drought and flood episodes is included and the extreme hydrometeorological conditions are examined within an extended historical context. Finally, the recent exceptional conditions are reviewed in the light of observational evidence for trends in temperature, rainfall, river flow and aquifer recharge patterns.

The report is aimed at a broad audience; web links are provided to source material and footnotes provide technical guidance where it is considered useful. Locations of many of the rivers and monitoring sites mentioned in the report are shown on the Location Map (page 50).

Except where indicated otherwise the meteorological and hydrological data featured in this report have been supplied by the National River Flow Archive (Centre for Ecology & Hydrology), the National Climate Information Centre (Met Office) and the National Groundwater Level Archive (British Geological Survey).

Final validation of a significant proportion of the hydrometeorological data featured in this report has yet to be completed; correspondingly, the data may be subject to future revision.

2010-12 IN SUMMARY

The 2010-12 period across much of the UK was characterised by climatic conditions close to the extreme range captured in instrumental records which extend back several hundred years. This review focuses on the impact of the extended rainfall deficiencies which climaxed in the spring of 2012 and the subsequent dramatic termination of the drought, heralding widespread and sustained flooding across large parts of the country.

The 2010-12 drought

Limited rainfall, particularly the deficiencies over successive winter half-years, was the primary driver of the drought conditions which afflicted many parts of the country over the 2010-12 period. Spatial and temporal variations in rainfall were large with notable regional drought episodes extending from less than six to more than 24 months. There was, however, an absence of hot, dry summers which are normally a primary component in the public's perception of drought. This, together with the important, but largely hidden, decline in groundwater levels tended to mask the serious nature of the decline in water resources over the two years following the winter of 2009/10.

In the first half of 2010, rainfall deficiencies were most severe in north-west Britain, triggering the introduction of a hosepipe ban across north-west England in June. This regional drought subsequently moderated but in 2011 an extreme exaggeration in the north-west to south-east rainfall gradient across the UK shifted the primary focus of water resources concern to southern Britain and, thence, much of central, southern and eastern England where concentrations of population, intensive agriculture and commercial activity generate the highest water demand.

Exceptionally dry soils through the growing season of 2011 impacted widely on agriculture and meagre runoff and aquifer recharge through the following winter ensured that the drought achieved a particular severity in relation to water resources through the early months of 2012. Following England's lowest 24-month rainfall (for periods ending in March) in at least 100 years, a number of major reservoirs in England and Wales reported their lowest early-April stocks on record; many farm reservoirs had also failed to fill through the winter half-year of 2011/12.

Through its latter phases the drought was generally most intense in those parts of England where groundwater is a major source of water supply. Failures of wells and springs increased through the second half of 2011 and, following England's second lowest rainfall for successive winter half-years, groundwater levels in many Chalk and limestone outcrop areas were approaching, or below, seasonal minima by the early spring of 2012.

Near average summer rainfall (and mainly near or below average summer temperatures) ensured that the minimum river flows recorded during 2010 and 2011 were generally unremarkable, but by the early months of 2012 accumulated runoff totals were exceptionally depressed in many regions. In a series from 1961, only during the protracted droughts of 1990-92 and 1995-97 have 24-month runoff accumulations for England & Wales fallen below those recorded in 2010-12. At a national scale, runoff for March in 2012 was the lowest on record and, as more springs continued to fail, the associated contraction in the stream network was as severe, for the time of year, as any experienced in at least the last 50 years. This, together with the associated loss (albeit temporary) of aquatic habitat, the desiccation of wetlands, low oxygen levels in rivers, limited effluent dilution and the appearance of algal blooms underlined the environmental and ecological stress that was a defining characteristic of the drought.

In the early spring of 2012 soils across much of the country were at their driest on record for the time of year and, with river flows, reservoir stocks and groundwater levels in the drought-affected regions seasonally depressed, hosepipe bans affecting 20 million consumers were introduced in early-April. With the expectation of the normal seasonal rise in evaporation rates through the late spring and summer, no early recovery in runoff and aquifer recharge rates was anticipated. The outlook for water resources, agriculture and the aquatic environment was fragile across large parts of central, eastern and southern England.

A remarkable hydrological transformation

Early-April 2012 witnessed a decisive change in synoptic patterns; the Jet Stream moved south allowing a persistent sequence of very active Atlantic frontal systems to cross the UK. April rainfall totals were the highest on record in many areas and, for England & Wales, the April-June period was the wettest in a historical series which extends back to 1766. The extreme rainfall initiated a dramatic hydrological transformation which, at a critical time for water resources, rapidly reversed the normal seasonal decline in runoff and, subsequently, recharge rates. As a consequence, the focus of hydrological concern switched rapidly from drought stress to flood risk.

The agricultural drought terminated as soils wetted-up through the late spring in most areas. However, the subsequent persistence of near-saturated soil moisture conditions limited access to farmland, retarded crop development, reduced yields and restricted harvesting opportunities. The saturated soils also made most rivers very responsive to the summer deluges; runoff from England & Wales, having been below previous early-April minima, increased dramatically to exceed its previous late-April maxima.

Remarkably high runoff rates were maintained throughout the late spring and much of the summer. Instances of fluvial and flash flooding were common and, subsequently, flood risk was exacerbated by groundwater flooding in vulnerable areas. The seasonally extreme runoff rates helped to rapidly replenish reservoir stocks and estimated overall stocks for England & Wales exceeded previous maxima in each month from June to September. More remarkably, average stocks through the summer half-year of 2012 were greater than for any winter half-year in a series from 1989. The exceptional runoff initially benefited desiccated wetlands and helped to extend the drainage network into the previously dry headwater reaches of many rivers. By May however, the saturated catchments and widespread floodplain inundations presented further problems for wildlife, the environment, agriculture and many leisure activities.

The record rainfall and the associated near-saturated soil moisture conditions facilitated notably high aquifer recharge rates through the summer half-year – triggering seasonally extreme recoveries in groundwater levels. Particularly rapid recoveries characterised most limestone aquifers and record late summer groundwater levels were widely reported. However, water tables remained depressed in a number of slowly responding aquifer units (the Permo-Triassic sandstones of the Midlands in particular) until much later in the year.

After a brief respite in August and early-September, floodplain inundations were again common and sustained. Whilst extreme flows in individual river basins were less common than the record national and regional runoff might imply, the scale of the flooding was remarkable for the summer half-year (April-September). Subsequently, spells of very wet weather in late-November and December resulted in a further and more extensive phase of flooding, contributing to an estimated total of 8,000 properties flooded in 2012 as a whole. This figure would have been very much higher in the absence of flood defences.

Rapid hydrological recoveries following drought are not particularly rare and the close juxtaposition of drought and flood episodes has, as in 1947 and 1976 for example, had a more severe impact than was the case in 2012. What sets 2012 apart is that the water resources recovery and persistence of exceptionally high rates of runoff were initiated and sustained through the late spring and summer. In this context, 2012 has no close modern parallel.

The UK's exceptionally long climatological records are punctuated by occasional extreme hydrological episodes but, with temperatures increasing beyond their historical range over the last 50 years, the sequence of major flood and drought events through the early years of the 21st century has fuelled speculation that floods and droughts are increasing in both frequency and magnitude in a warming world. However there is, as yet, limited convincing evidence for any substantial long-term trends in rainfall, river flows (including flood magnitude) and groundwater recharge.

The 2010-12 period served to demonstrate the inherent variability of the UK's climate and underlined our continuing vulnerability to sustained periods of rainfall deficiency or excess. The three years also demonstrated the degree to which river and water management strategies have increased resilience to drought and flood episodes. There is a continuing need to extend the knowledge base and modelling capabilities to further develop these strategies in order to reconcile the, often competing, demands on limited water resources, whilst balancing the need to protect property from flood risk with the need to maintain a healthy aquatic environment for wildlife. A prerequisite for improved strategies to address the increasingly complex range of drought and flood impacts is a fuller understanding of how rainfall, runoff and aquifer recharge patterns are changing in a warming world. Maintaining effective hydrometeorological monitoring programmes is essential to better understand drought and flood causation, place contemporary extremes in a historical context and, crucially, quantify climate-driven trends in rainfall, runoff and aquifer recharge.

THE 2010-12 DROUGHT

Preamble

Across much of the world, droughts constitute one of the worst natural disasters – posing a real and continuing threat to lives and livelihoods – but there is no generally accepted definition of exactly what drought comprises. This is a reflection of their multi-faceted nature, their wide range of impacts and the fact that the various manifestations of drought stress vary both spatially and temporally. In the UK, for example, soil moisture conditions through the growing season are of primary importance to agriculture whilst winter rainfall is the principal determinant of the water resources outlook, particularly where groundwater is a major source of water supply. In addition, falling water levels in rivers and wetlands can generate substantial environmental and ecological stress.[1] Thus whilst a lack of rainfall is generally recognised as a key characteristic of droughts[2], developing rigorous and objective procedures for identifying their onset and termination, monitoring changes in their severity and indexing the magnitude of their impacts, remains a considerable challenge.[1,3]

In this report, a hydrometerological framework is used to examine the 2010-12 drought's development and severity; an overview of its impacts is presented at the end of the section.

Rainfall

Synoptic background

A key causative factor of the drought conditions in 2010-12, as in other years, was the persistence of blocked weather patterns which diverted rain-bearing frontal systems away from the British Isles, or parts thereof.[4,5] This blocking was particularly apparent during the winter of 2009/10 (and continuing into the following summer) when there was a marked absence of moist westerly airflows[a], and again in December 2010. The weather patterns were slightly different in 2011: the Jet Stream and associated rain-bearing fronts often tracked across the north of the UK (see Figure 1) but these fronts tended to weaken as they moved south-east. Frequently there was little or no rain across south-east England, which was often under the influence of high pressure from the near-continent. The continuing dominance of high pressure through the early months of 2012 ensured that drought conditions were exceptionally severe by the early spring.

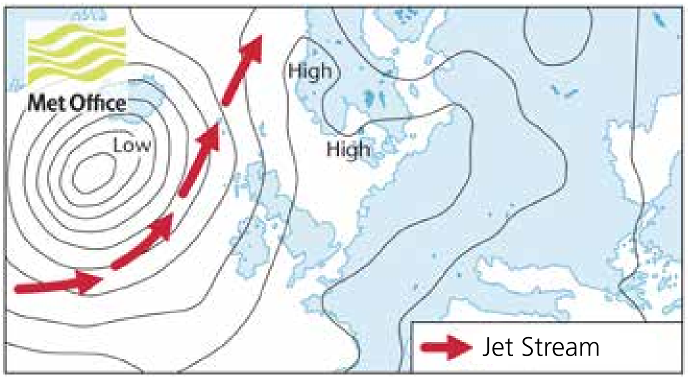

Figure 1 *Predominant path of the Jet Stream during the 2010-12 drought*

Development of the drought

UK droughts typically display considerable variations in intensity over time and between regions; such contrasts were particularly marked over the 2010-12 period. The spatial and temporal variations in the drought's development and decay can be tracked over the three-year period using Figures 2-4. Figure 2 shows regional monthly rainfall departures from the 1971-2000 average[b], Figure 3 maps departures from the average rainfall for a number of key timespans and Figure 4 uses rolling three- and six-month timeframes to chart changes in the regional magnitude of the rainfall deficiencies and surpluses. The Figures confirm the broad geographical range of drought conditions in the early summer of 2010 and the intensity of the rainfall deficiencies across England & Wales in the spring of 2011 and the early spring of 2012. Assessments of the rarity of the rainfall deficiencies for a selection of timespans are given in Table 1 and are discussed on page 10.

Generally, the drought's origin may be traced back to a notably dry December across north-west Britain in 2009. Rainfall deficiencies increased through the late winter and the UK's driest spring since 1984 but drought concerns then eased greatly through the late summer and early autumn of 2010. Subsequently however, the UK's driest December since 1963 heralded a further and more extensive phase of the drought. 2011 witnessed an unprecedented exaggeration in the north-west/south-east rainfall gradient across the UK[c]

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[a] The blocked conditions in winter 2009/10 were associated with a marked southerly shift in the Jet Stream, with associated frontal systems and wet weather far to the south; Gibraltar recorded its wettest winter in a composite series from 1813.

[b] Generally, comparisons with previous month, seasons and years - and the derivation of return periods - are based on rainfall (and temperature) series from 1910 derived and managed by the National Climate Information Centre (Met Office). The national and regional series are based upon 5 km grids, produced using the methods of Perry & Hollis (2005)[6]. The monthly England & Wales Precipitation series (EWP) from 1766[7] provides a longer-term perspective.

[c] Based on comparisons of annual rainfall totals for western Scotland and the Anglian Region from 1910.

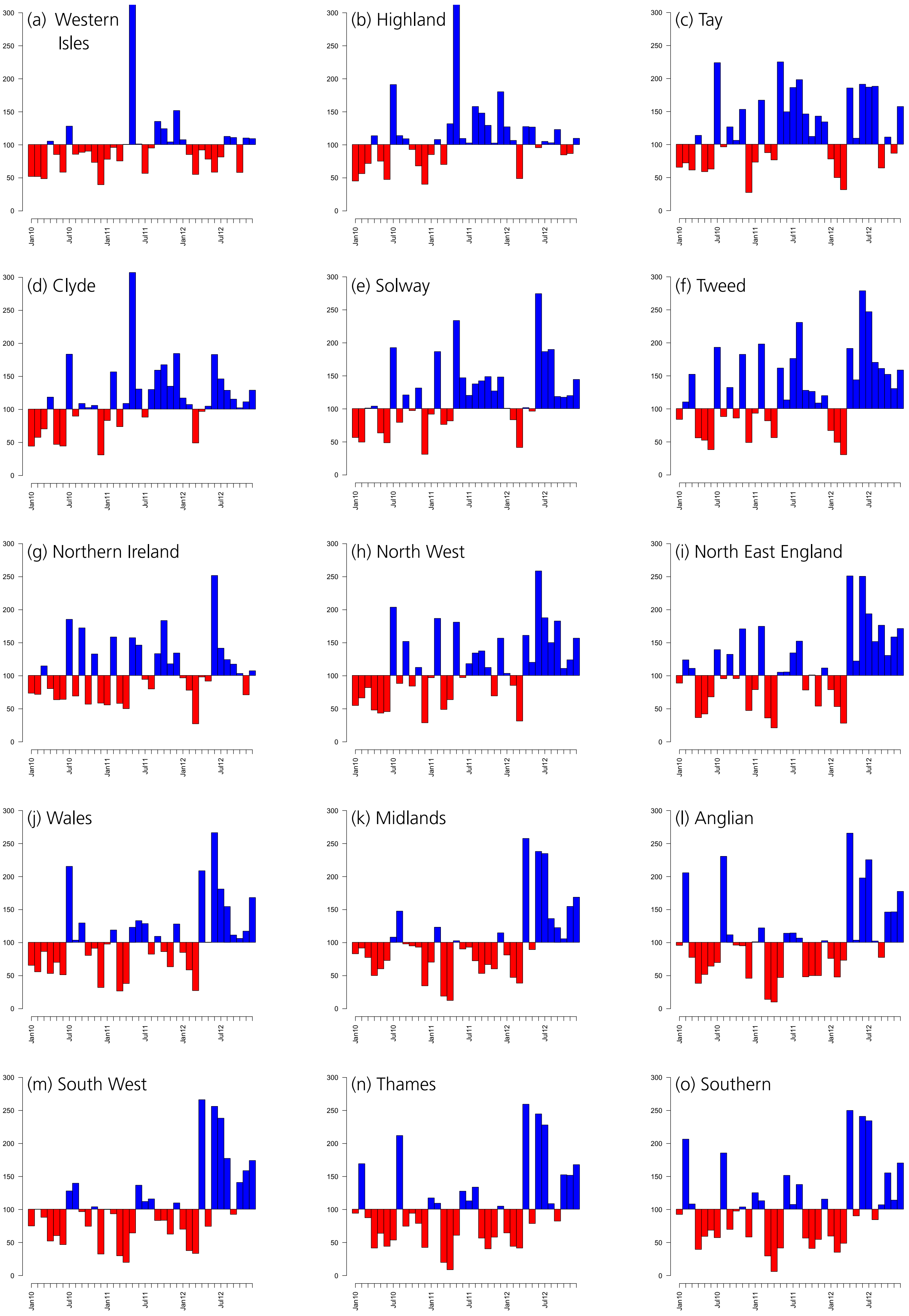
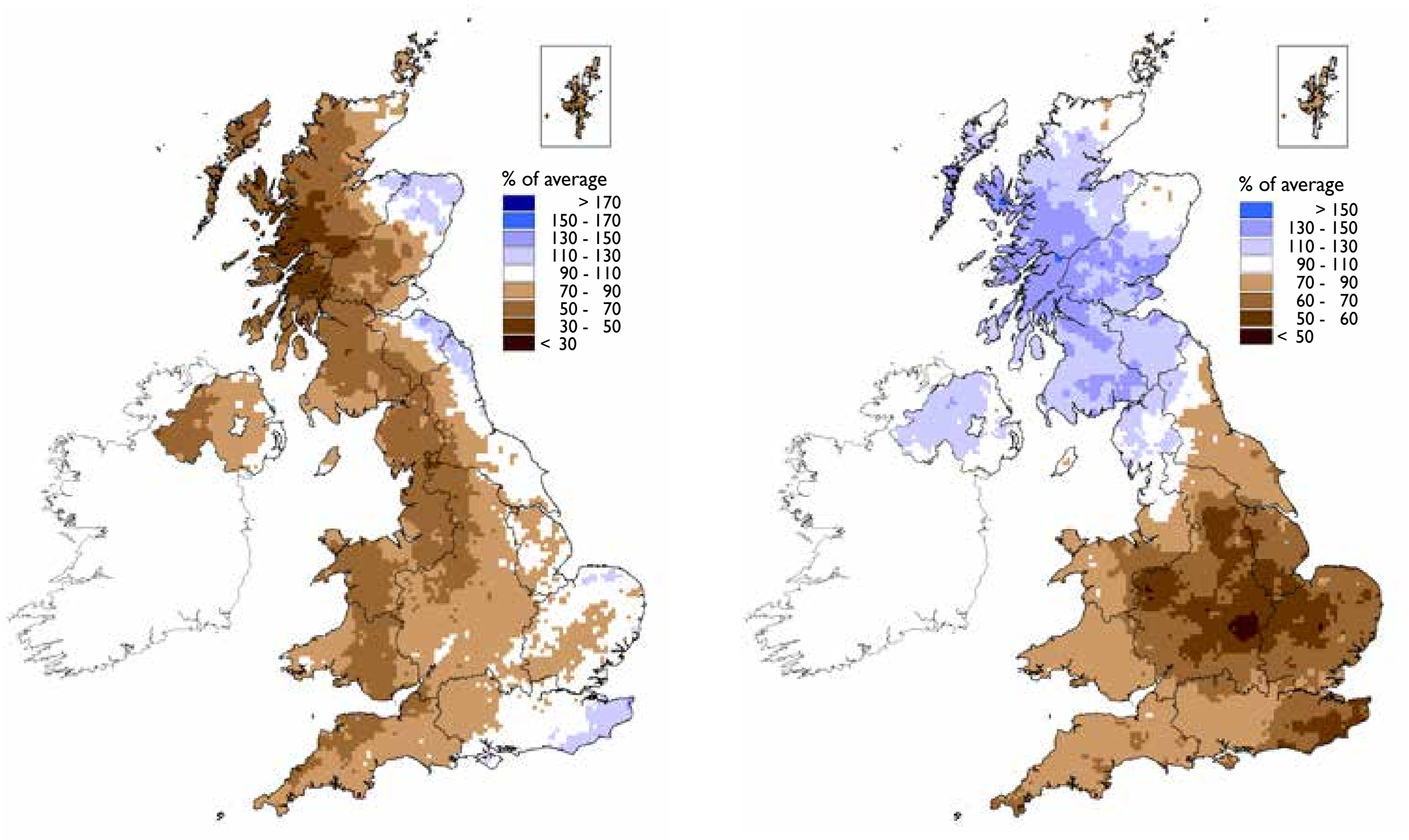
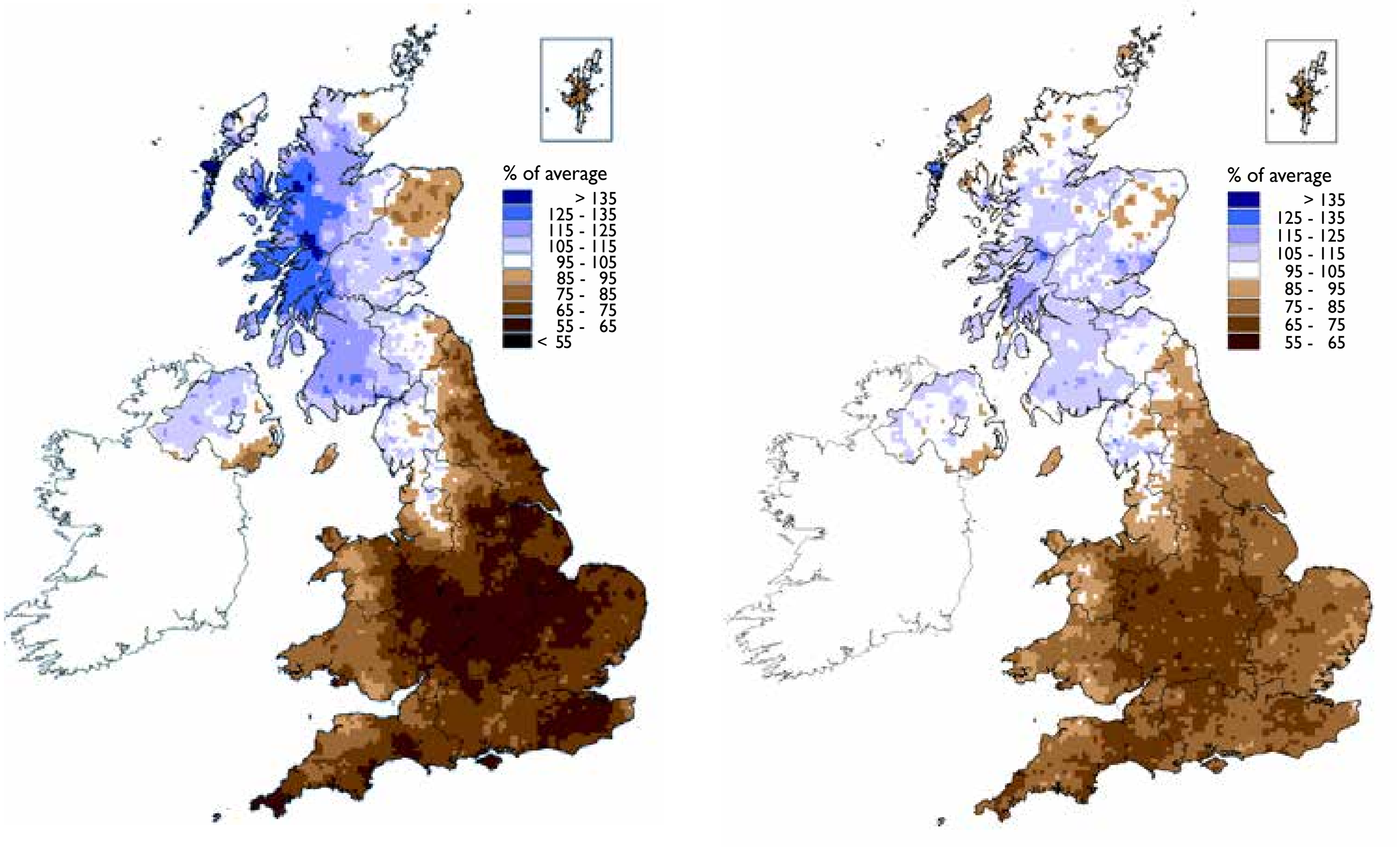


Figure 2 *2010-12 monthly rainfall departures (%) from the 1971-2000 average*



(a) December 2009 - June 2010

(b) March 2011 - November 2011

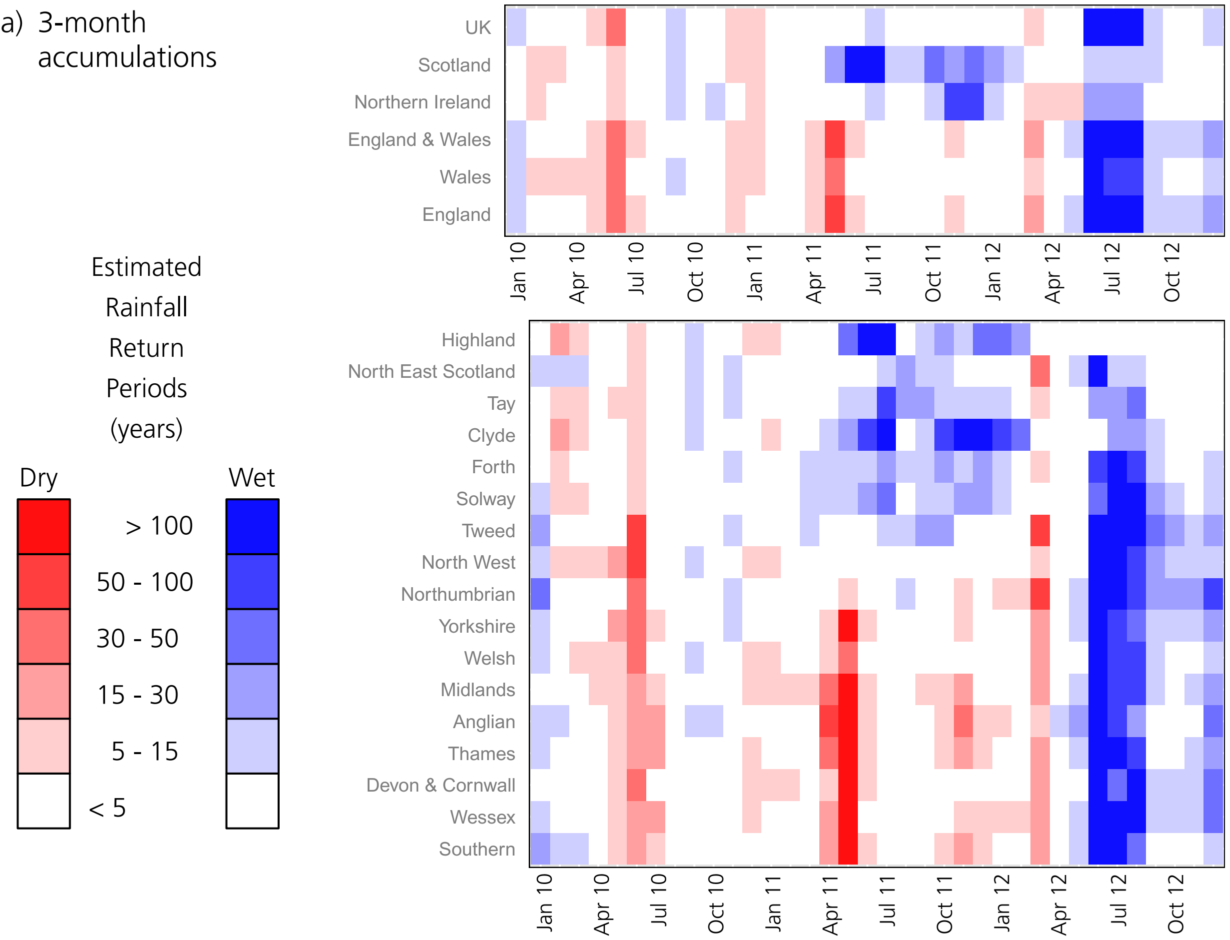


(c) March 2011 - March 2012

(d) April 2010 - March 2012

Figure 3 *Rainfall anomaly maps (% of 1971-2000 average) for selected accumulation periods during the 2010-12 drought*

(a) 3-month accumulations



(b) 6-month accumulations

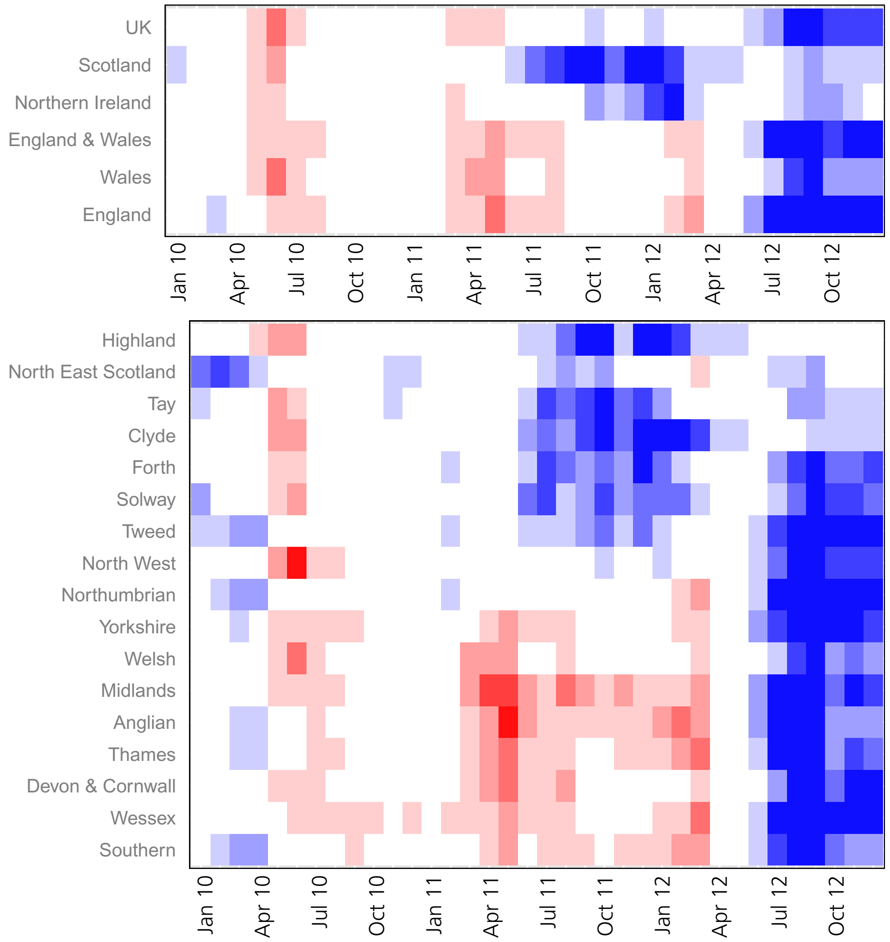


Figure 4 *Estimated rainfall return periods for rolling three- and six-month accumulations, 2010-12*

Note: areal extent of the Wales and Welsh regions are considerably different

Table 1 *National and regional rainfall totals and associated return periods for selected durations during 2010-12*

Area	**Rainfall**	**Jan10 – Jun10**		**Apr10 – Apr11**		**Mar11 – Nov11**		**Mar11 – Mar12**		**Apr10 – Mar12**	
			RP		*RP*		*RP*		*RP*		*RP*
United Kingdom	mm	360		1020		787		1163		2097	
	%	73	25-40	89	5-10	103	2-5	100	2-5	98	2-5
England	mm	291		715		453		677		1361	
	%	77	8-12	83	10-20	77	20-30	77	30-50	84	25-40
Scotland	mm	455		1465		1317		1931		3212	
	%	70	15-25	96	2-5	132	>100	123	70-100	112	10-20
Wales	mm	400		1208		797		1233		2379	
	%	65	30-50	84	10-20	84	8-12	84	10-15	88	10-20
Northern Ireland	mm	403		1083		911		1278		2271	
	%	79	5-10	92	5-10	116	5-10	106	2-5	103	2-5
England & Wales	mm	306		783		500		753		1501	
	%	74	10-20	83	10-20	78	15-25	79	25-40	85	20-35
North West	mm	302		1151		879		1315		2375	
	%	58	>100	93	2-5	105	2-5	104	2-5	102	2-5
Northumbria	mm	332		858		593		785		1586	
	%	86	2-5	98	2-5	98	2-5	88	8-12	97	5-10
Midlands	mm	263		615		347		548		1145	
	%	73	10-15	77	20-35	63	>100	68	>100	76	>100
Yorkshire	mm	291		719		459		686		1381	
	%	76	8-12	84	10-15	78	10-20	79	15-25	86	15-25
Anglian	mm	239		534		285		435		957	
	%	85	2-5	83	8-12	62	60-90	68	70-100	80	25-40
Thames	mm	272		563		345		508		1056	
	%	82	2-5	76	15-25	67	30-50	68	50-80	77	50-80
Southern	mm	339		672		370		569		1220	
	%	96	2-5	82	8-12	66	50-80	69	80-120	80	30-50
Wessex	mm	298		675		466		673		1319	
	%	74	5-10	74	40-60	77	15-25	73	40-60	77	>100
South West	mm	403		984		627		980		1919	
	%	72	8-12	78	20-30	77	15-25	76	30-50	81	50-80
Highland	mm	498		1640		1532		2381		3784	
	%	65	10-20	90	2-5	131	50-80	126	40-60	110	8-12
North East	mm	448		1126		835		1097		2103	
	%	103	2-5	112	2-5	120	2-5	107	2-5	112	2-5
Tay	mm	417		1385		1230		1634		2863	
	%	70	10-20	104	2-5	142	>100	118	15-25	114	8-12
Forth	mm	393		1260		1078		1443		2551	
	%	76	5-10	106	2-5	136	50-80	117	10-20	114	10-15
Tweed	mm	378		1028		891		1143		2071	
	%	86	2-5	102	2-5	131	10-15	112	2-5	110	2-5
Solway	mm	438		1483		1300		1841		3165	
	%	70	10-20	100	2-5	133	25-40	121	30-50	114	10-20
Clyde	mm	469		1738		1668		2498		4018	
	%	62	20-35	95	2-5	140	>100	132	>100	117	30-50

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

Note: the return period estimates are based on data provided by the Met Office and reflect climatic variability since 1910; they also assume a stable climate. 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 details of methodology used see reference Tabony (1977)[2] (see Figure 5). With most rain-bearing frontal systems following tracks across northern Britain, parts of central and eastern England registered their driest year since 1921 with annual totals falling below 400 mm. By contrast, totals locally exceeded 4,000 mm in the western Highlands, and Scotland recorded its wettest year in a series from 1910.

Across southern Britain, rainfall deficiencies increased considerably through the spring of 2011, the driest since 1893[4] in the 247-year England & Wales Precipitation series (EWP)[7]. Although summer rainfall was modestly above average, drought conditions re-intensified through the notably dry autumn. Drought concerns were becoming increasingly focused on central, southern and eastern England with well above average rainfall required in early 2012 to avoid very substantial drought stress. In the event, rainfall deficits increased markedly through the first three months of 2012. February and March were particularly dry: high pressure across Europe largely confined February's wet weather to the north and west and also dominated during March. Large swathes of the country received less than half the average rainfall for each month[4] and March was the driest for the UK since 1953. By the end of March 2012, 14 of the previous 24 months had seen less than 70% of average rainfall across Lowland England (see Figure 5 for its delineation) with ten of these below 55%.

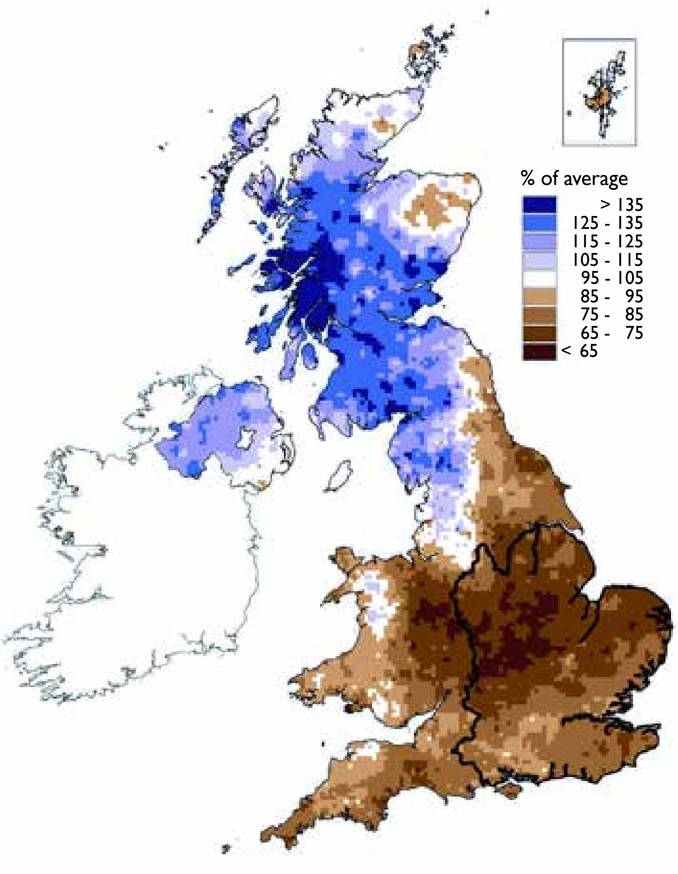


Figure 5 *Rainfall anomaly map (% of 1971-2000 average) for 2011*

Note: black line delineates Lowland England

Severity of the rainfall deficiencies

Longer term rainfall deficiencies generally peaked over the 24-28 month period ending in March 2012 when notably severe drought conditions affected most of central England, and extended across neighbouring regions. There were also several important shorter regional drought episodes within that overall timeframe, including:

- December 2009 / January 2010 to June 2010 (north-west England extending into western Scotland and Wales);
- December 2010 to May 2011 (Anglian region, extending across central areas and into the South West);
- April to November 2011 (for the Midland region rainfall was the lowest in the National Climate Information Centre (NCIC) series, which begins in 1910).

The January to June rainfall total in 2010 was the lowest since 1953 at the national scale, and since 1929 in the North West England and North Wales series. In Scotland, the Western Isles recorded their lowest December-June rainfall since 1939 and, together with other parts of western Scotland, experienced several further dry episodes over the following two years.

For 24-month periods ending in March 2012, the 2010-12 England & Wales rainfall total was the fourth lowest in the NCIC series; only 1995-97 was substantially drier in this timeframe. In the longer EWP series, since the 1850s only 1995-97, 1990-92 (marginally) and 1933-35 have recorded lower 24-month totals beginning in April and only four have been lower for any start month since the early 19th century[d] (see Table 2). Across a large part of central and southern England, and the Midlands particularly, the drought achieved its greatest intensity with many areas receiving less than 75% of average rainfall over the 24 months (see Figure 3d). This period was the second driest in this timeframe (in a series from 1910) and, for Lowland England, the overall rainfall deficit was the equivalent of approximately half a year's average annual rainfall.

On the basis of rainfall deficiencies accumulated over 12-24 months duration, the 2010-12 drought ranks in the ten most significant events across England & Wales in the last 100 years, and for Lowland England – particularly parts of the Midlands – probably within the first six. Key sustained droughts of the last century

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[d] The sparse nature of the early raingauge network implies significant uncertainty in areal rainfall assessments but comparable, or drier, extended droughts occurred in 1780-81, 1783-85, 1801-03 and 1806-08.

Table 2 *Minimum non-overlapping 24-month rainfall totals for England & Wales since 1810*

Rank	End Month	Rainfall total (mm)	% of 1971-2000 average*
1	Sep 1855	1394	75.2
2	Apr 1997	1399	75.5
3	Oct 1934	1431	77.2
4	Feb 1992	1465	79.0
5	**Mar 2012**	**1506**	**81.2**
6	Nov 1845	1507	81.3
=7	Jan 1923	1514	81.7
=7	Jan 1889	1514	81.7
9	Sep 1976	1515	81.7
10	Jun 1974	1524	82.2

**1971-2000 average 24-month rainfall given here is twice average annual rainfall for 1971-2000, which is 927 mm*

across England & Wales include those of 1920-21, 1933-34, 1975-76, 1990-92 and 1995-97[8]. Of these, the droughts of 1920-21 and 1975-76 stand out in terms of intensity with only around 60% of average rainfall across Lowland England. For England & Wales as a whole, the rainfall total for May 1975 to August 1976 ranks as driest in the EWP series for any 16-month period by a considerable margin[9]. Nonetheless, the overall rainfall deficiency for Lowland England was only 30 mm greater than that built up over the full span of the 2010-12 drought[4] (see Table 3).

The temporal distribution of the rainfall deficiencies in 2010-12 contributed substantially to the drought's character and range of impacts – especially in relation to water resources. In particular, whilst rainfall totals over the summers of 2010 and 2011 were well within the normal range, rainfall over the winter half-years was meagre. For England & Wales, the 2010-11 and 2011-12 October-March periods, taken together, were the second driest in the last 100 years behind only 1962-64 (see Figure 6). The lack of winter half-year rainfall was the primary cause of the water resources stress experienced through the latter stages of the drought; it also implied that generally the drought was considerably more severe in runoff and aquifer recharge terms than rainfall terms.

Table 3 *Droughts across Lowland England since 1910, defined by rainfall deficit*

Start month	End month	Duration (months)	Total rainfall (mm)	Deficit (mm)	% of 1971-2000 average
Apr 1995	Apr 1997	25	1004	422	70
Aug 1920	Dec 1921	17	630	379	62
Mar 1990	Feb 1992	24	1006	370	73
May 1975	Aug 1976	16	541	356	60
Apr 2010	**Mar 2012**	**24**	**1050**	**326**	**76**
Apr 1933	Nov 1934	20	829	315	72
Aug 1947	Sep 1949	26	1181	312	79
Feb 1943	Jun 1944	17	662	281	70
Aug 1972	May 1974	22	995	277	78
Aug 1988	Nov 1989	16	702	237	75
Dec 1963	Feb 1965	15	639	229	74
Nov 2004	Apr 2006	18	810	227	78

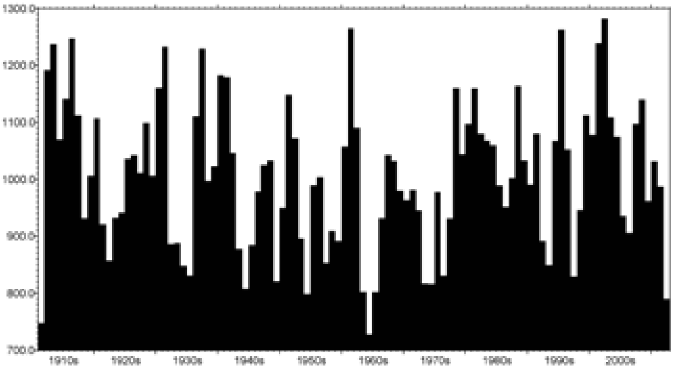

Figure 6 *Two-year October-March rainfall totals (mm), England & Wales*

Temperatures, evaporation and soil moisture

High temperatures, as in the summers of 1976, 1995 and 2003 – when heat stress directly impacted the elderly in particular – can be an influential factor in UK droughts. Normally however, it is the association between temperature and evaporation demands (and the corresponding soil moisture conditions) that is most influential in relation to drought development and decay.

Average temperatures for England & Wales over the 2010-12 period exhibited an enhanced degree of temporal variation. 2010 was the coldest year across England & Wales since 1987 – largely due to the winter of 2009/10 (the coldest nationally for 31 years) and freezing conditions during an exceptionally cold spell from late-November to late-December. Most other months of 2010 were warmer than average, but not exceptionally so. In contrast, spring and autumn 2011 (which included a seasonal heat-wave from late-September to early-October) were, respectively, the equal warmest and second warmest such seasons in the 353-year Central England Temperature (CET) series[10]. Winter 2011/12 was also warmer than average, while March 2012 was the warmest for the UK since 1957.

Evaporation[e] has a marked seasonal cycle in the UK but it is a conservative variable; normally annual potential evaporation (PE) and actual evaporation (AE) losses are within 10% of the long-term average at the national scale. For England, PE losses were average for 2010 as a whole, considerably above average in 2011 and appreciably below in 2012. By contrast, AE losses were considerably below average in 2010 and 2011 (Figure 7) but around 5% above average for 2012 as a whole. The differences are explained primarily by the development and decay of soil moisture deficits (SMDs[f]) throughout the 2010-12 period (Figure 8). SMDs departed very markedly from normal seasonal patterns and were a major contributory factor to the severity of drought conditions. This was particularly true in an agricultural context but was very influential also in limiting the length of the aquifer recharge season and restricting reservoir replenishment.

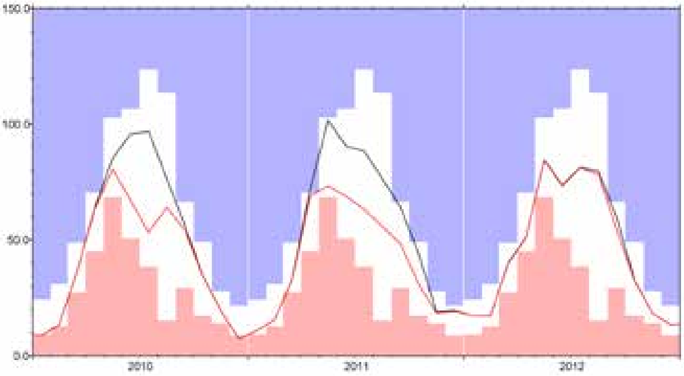

Figure 7 *Monthly potential evapotranspiration (black; mm) and actual evapotranspiration (red; mm) for England*

Note: unless otherwise stated, blue envelopes represent period of record maxima to 2009, red envelopes represent period of record minima to 2009, and a grey trace may be used to indicate period of record mean to 2009

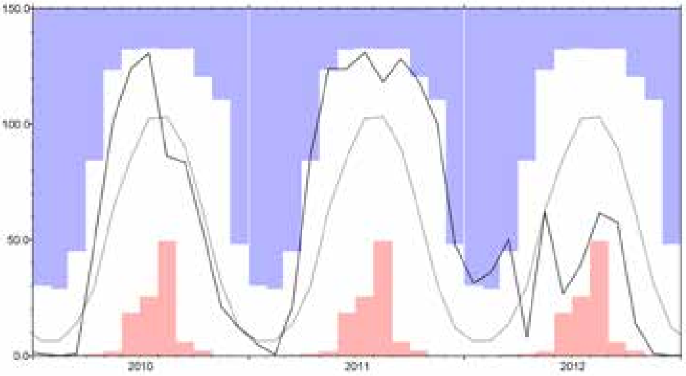

Figure 8 *End-of-month soil moisture deficits (mm) across Lowland England*

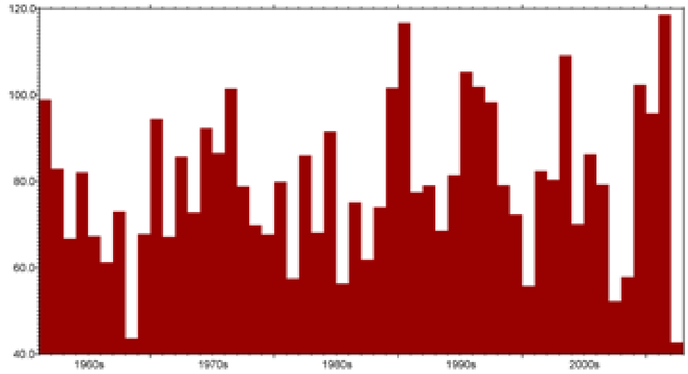

Figure 9 *Average April-September soil moisture deficits (mm) across Lowland England*

SMDs exceeded the monthly average for lengthy periods during the first half of 2010 and, subsequently, exceptionally dry soil moisture conditions through the spring of 2011 substantially intensified drought conditions over wide areas. For Lowland England the average SMDs for 2011 as a whole, and for the summer half-year (see Figure 9), exceeded the previous maximum in a 52-year series. Evaporative demands through the winter half-year of 2011/12 remained within the normal range but the driest October-March for England & Wales since 1975/76 resulted in SMDs tracking close to monthly maxima throughout the winter and, at the national scale, eclipsing the previous maximum for late-March by a considerable margin. More significantly in a water resources context, average end-of-March SMDs across the outcrop areas of the Chalk were also the highest on record (Figure 10).

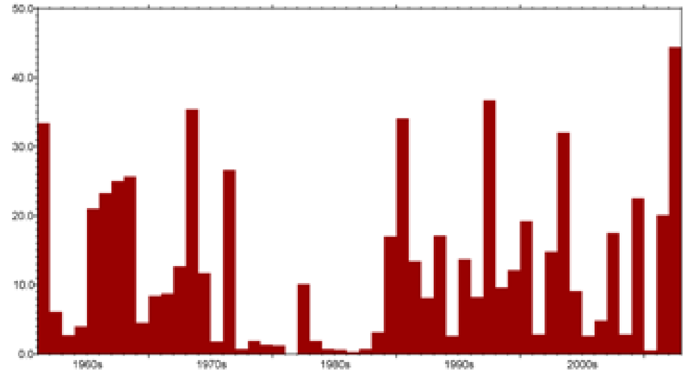

Figure 10 *End-of-March soil moisture deficits (mm) across the Chalk outcrop*

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[e] Evaporation may occur directly from open water surfaces, from the soil or as transpiration from plants. Potential evaporation (PE) is the maximum evaporation that would occur from a continuous vegetative cover amply supplied with moisture. Temperature, particularly during the late spring and summer, is the primary influence on evaporative demands, but wind speed, sunshine hours, humidity and patterns of land use are all contributory factors. Given normal rainfall, the increasing temperatures and accelerating evaporative demands through the spring lead to a progressive drying of the soil and the creation of what is termed a soil moisture deficit (SMD). Eventually, the ability of plants to transpire at the potential rate is reduced as a result of the drying soil conditions, the associated reduced capability of plants to take up water, and the measures they take to restrict transpiration under such conditions. Thus in the absence of favourable soil moisture conditions actual evaporation (AE) rates fall below corresponding PE rates, appreciably so during dry summers.

[f] Most of the evaporation and soil moisture data featured in this report derive from MORECS[11] and assume a grass cover.

River flows

Development of the drought

Significant runoff deficiencies developed initially through the early months of 2010 across north-western parts of the UK and achieved their greatest magnitude across southern Britain two years later. Within this timespan, the regional variations in runoff deficiencies varied very substantially.

Figure 11 illustrates daily flow patterns for 2010-12 at a national scale and Figure 12 features hydrographs for a selection of index rivers across the UK. In the late autumn of 2009 runoff rates were exceptionally high across most of the country but steep recessions, accelerated by frozen catchment conditions through the early winter, resulted in exceptionally low mid-January flows in western Scotland and Northern Ireland. After spate conditions at the end of March 2010, steep recessions continued with only brief interruptions for the next three months, resulting in notably low flows in May and June over wide areas.[5,12] Flows in many rivers (from the Nevis in northern Scotland to the Cynon in south Wales) fell below previous late-June minima. However, catchments in the western uplands are generally steep with a thin soil cover and as a consequence, river flows responded smartly to the sustained July rainfall. Subsequently, runoff rates generally remained within the normal range, albeit mostly below average, until November when further lengthy recessions heralded well below average runoff through the winter of 2010/11 across southern Britain.

The drought became much more regionally focused through 2011. Whilst annual runoff for Scotland in 2011 was the highest in the 52-year national series, outflows from Lowland England[9] were the third lowest (after 1976 and 1997) on record. Recessions were again steep and protracted through the spring; in a substantial proportion of index rivers late-April flows fell below previous minima for the time of year. Entering the summer, river flows were most depressed in a zone from south Wales to western Scotland.

Summer flows generally remained well above drought minima but in much of eastern, central and southern England, the very dry autumn soils in 2011 ensured only a very weak seasonal recovery in runoff. Correspondingly, the drought entered a more intense phase as runoff rates fell increasingly below the normal seasonal range and accumulated runoff deficiencies became exceptional. In Northern Ireland, runoff over the March-September period was the lowest on record for the Annacloy (in a series from 1979), and annual runoff totals for 2011 fell below previous minima for a number of rivers in England (including the Kenwyn, Soar and Teme).

By early 2012, many spring-fed streams and rivers had recorded 20 or more successive months with below average flows. The weakness of the seasonal runoff recoveries through the winter of 2011/12, in part a consequence of declining groundwater contributions to river flows, was then exacerbated by the very low rainfall through February and March 2012. Outflows from Lowland England, with the exception of two isolated occasions, had remained below the long-term daily average for over a year (see Figure 11e) and fell below previous daily minima by mid-March. In the final week of March outflows from Great Britain as a whole also declined below previous minima for the time of year.

Severity of the runoff deficiencies

Rainfall patterns across the UK exhibit only modest seasonal contrasts but the impact of evaporation losses imposes a substantially greater seasonality on river flows. For Lowland England for example, mean runoff over the summer (June-August) is on average only a little more than 30% of that for the winter (December-February). Correspondingly, a defining feature of most droughts is the exceptionally low runoff rates which normally characterise the summer and early autumn.

Throughout the 2010-12 drought many existing seasonal minimum flows were eclipsed during the winter, spring and autumn but annual minimum flows were not especially depressed and the outstanding minimum flows registered during the extreme drought of 1975-76[9] were not closely approached. There were some exceptions: Table 4 confirms that 60-day minima for 2010 were very low in some largely impermeable western catchments (e.g. the Ribble) and also notably rare in a number of groundwater-fed streams in 2011 (e.g. the Rea Brook). 60-day minimum flows in 2012 were largely unexceptional but, importantly, all of the rivers in England & Wales featured in Table 4 closely approached, or fell below, previous minimum flows for late-March or early-April.

A convincing index of the drought's severity during its early phase is provided by accumulated runoff totals for catchments across much of western Britain (see Figure 13a). For the Nevis in the western Highlands of Scotland the December 2009 – June 2010 runoff was, remarkably, below any other seven-month accumulation in a series from 1982. In the January-June timeframe new minimum runoff accumulations were reported for many western index catchments; the very meagre flows in west-draining rivers contributed to the

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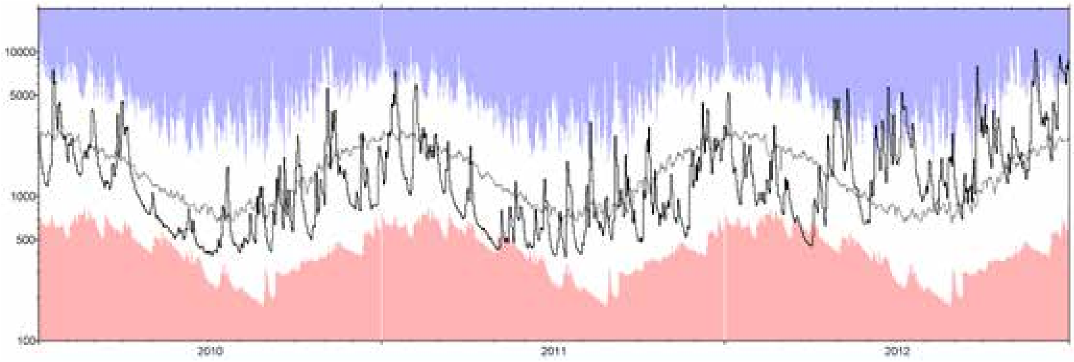
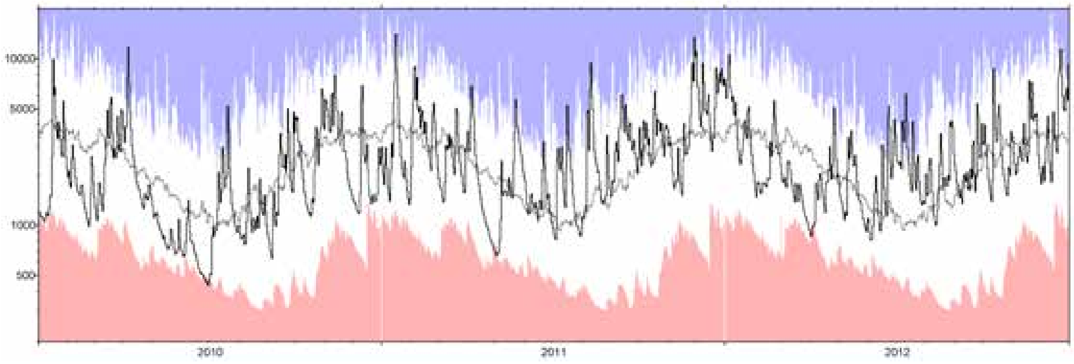
[9] National and regional runoff assessments are based on flows from a representative network of large river basins; the time series begin in 1961.

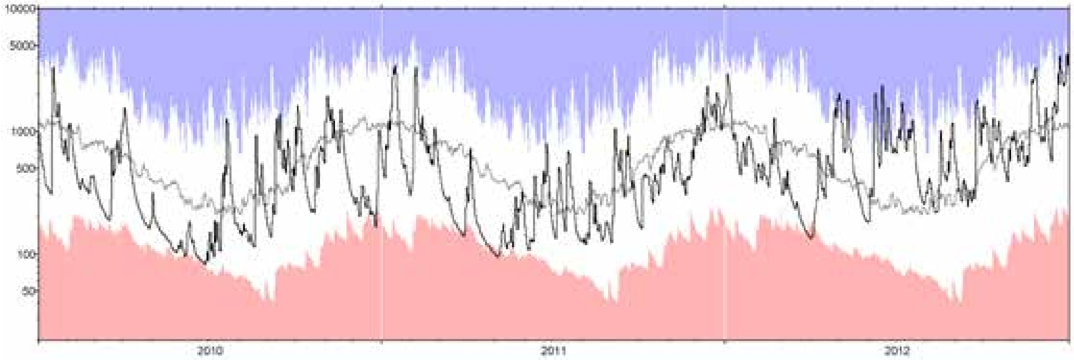
(a) England



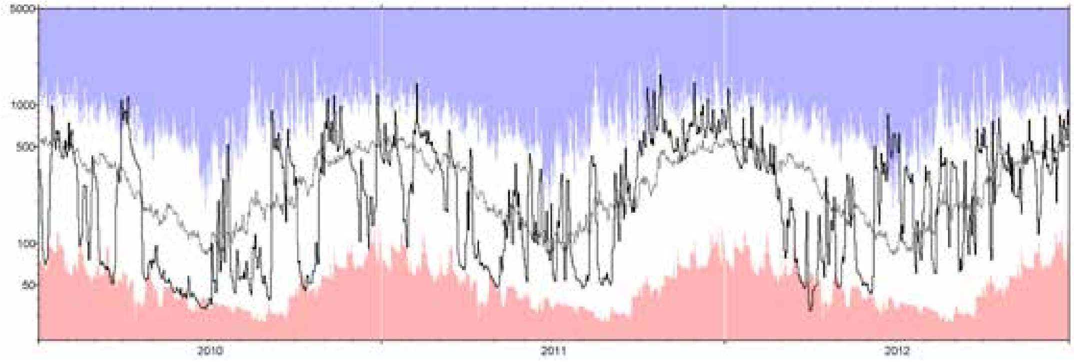
(b) Scotland



(c) Wales



(d) Northern Ireland



(e) English Lowlands

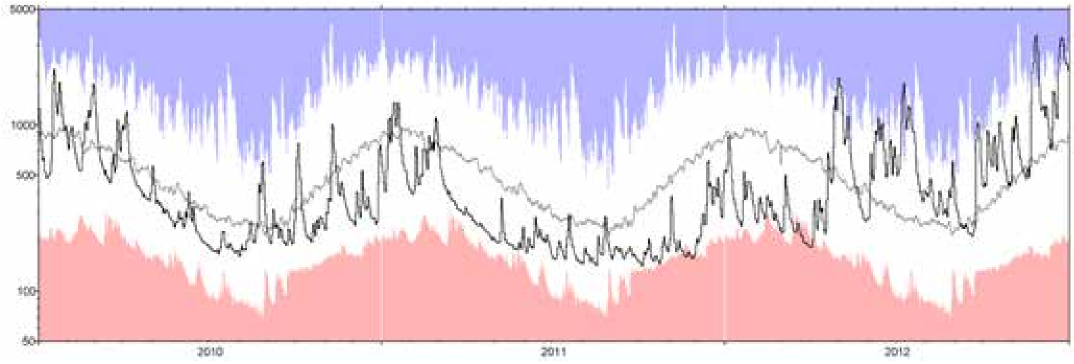


Figure 11 *Outflows (m^3 s^{-1}) from the constituent countries of the UK, and the English Lowlands*

Table 4 *Return periods of 60-day calendar year annual minimum flows*

River Name	Station Name	2010 Min ($m^3 s^{-1}$)	Estimated Return Period (years)	2011 Min ($m^3 s^{-1}$)	Estimated Return Period (years)	2012 Min ($m^3 s^{-1}$)	Estimated Return Period (years)
Ewe	Poolewe	8.43	2-4	11.65	< 2	4.57	15-25
Falloch	Glen Falloch	0.45	10-15	2.23	< 2	1.41	< 2
Mourne	Drumnabuoy House	7.78	5-8	24.84	< 2	22.32	< 2
Ribble	Samlesbury	4.20	20-25	9.29	< 2	18.11	< 2
Dee (Welsh)	New Inn	0.25	18-22	1.22	< 2	1.94	< 2
Rea Brook	Hookagate	0.31	2-3	0.15	40-80	0.76	< 2
Dove	Izaak Walton	0.52	5-8	0.39	15-20	1.53	< 2
Soar	Kegworth	3.98	4-6	3.20	18-22	4.75	< 2
Little Ouse	Abbey Heath	1.25	3-4	0.78	20-25	1.27	3-4
Mimram	Panshanger Park	0.37	2	0.22	8-12	0.22	8-12
Coln	Bibury	0.50	2-3	0.29	30-60	0.56	< 2
Chess	Rickmansworth	0.30	3	0.15	10-15	0.15	10-15
Avon	Amesbury	1.32	2-3	0.92	10-15	1.84	< 2
Tone	Bishops Hull	0.63	4-6	0.58	7-10	1.28	< 2

Note: methodology as described by Zaidman et al. (2003)[13]

lowest late-June runoff from Scotland on record (see Figure 11b). More significantly in a water resources context, estimated outflows from Wales over the January-June period were the lowest since 1976 and, in Cumbria, monthly mean flows for the Eden fell below previous monthly minima (in a series from 1967) in both May and June 2010.

Whilst runoff deficiencies generally declined rapidly across Scotland in 2011, they continued to build across much of southern Britain (see Figure 13b) through a year distinguished by the rarity of flows exceeding the daily average (see Figure 12l for example). Overall March-December outflows from Lowland England were appreciably below the previous minima and dwindling contributions from springs and seepages meant that runoff rates were especially depressed in a number of rivers draining largely permeable catchments. For example, the August-December runoff for the Little Ouse (Cambridgeshire) and the Winterbourne (Berkshire), was below that for any five-month sequence prior to 2011.

The degree of water resources stress across central and southern areas in early 2012 reflects the dearth of runoff over successive winter half-years (October-March). For Lowland England winter runoff for 2010-12 was the second lowest in the 52-year regional series (see Figure 14); one consequence was that 12-month runoff totals fell below 50% of average in the early months of 2012; only in 1975-76 have lower 12-month accumulations been recorded. For the Thames, where flow records begin in 1883, only in 1921-22 and 1943-44 have April-March runoff totals been lower than in 2011-12[h].

Across much of England & Wales runoff deficiencies reached a maximum in the early spring of 2012 (see Figure 13d). The Trent recorded 27 successive months with below average flows; Figure 11e confirms the limited period for which flows from Lowland England exceeded the long-term average throughout the drought. By the end of March 24-month runoff accumulations had fallen below any previously recorded (for any month) for a significant proportion of rivers – see Table 5. For Lowland England, the 2010-12 runoff deficiencies were notable across a wide range of timespans (Table 6) and appreciably greater than at the end of the shorter 1975-76 drought - but generally lower than the overall deficiencies built up through the very extended droughts of 1990-92 and 1995-97.

At the climax of the 2010-12 drought over three-quarters of UK index gauging stations[i] reported late-March/ early-April daily flows comparable with, or below, previous recorded minima; a very rare circumstance. As an increasing number of headwater streams dried up (see Plate I) through the early months of 2012, the associated contraction in the stream network was as severe (for the time of year) as any experienced in the last 50 years (and probably substantially longer). In early-April 2012 there was a justifiable expectation

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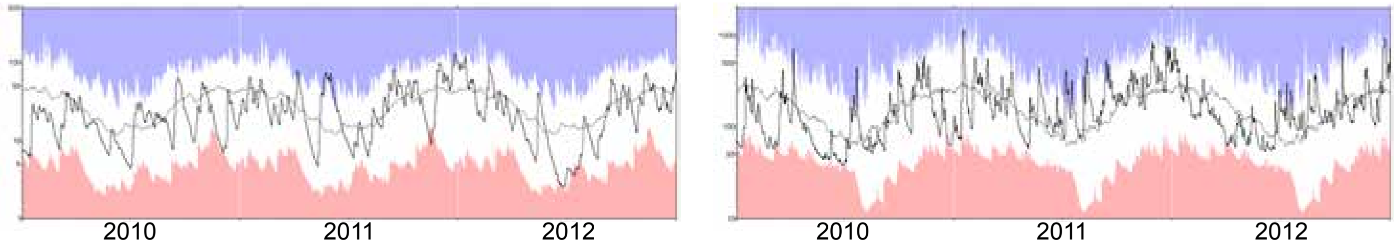
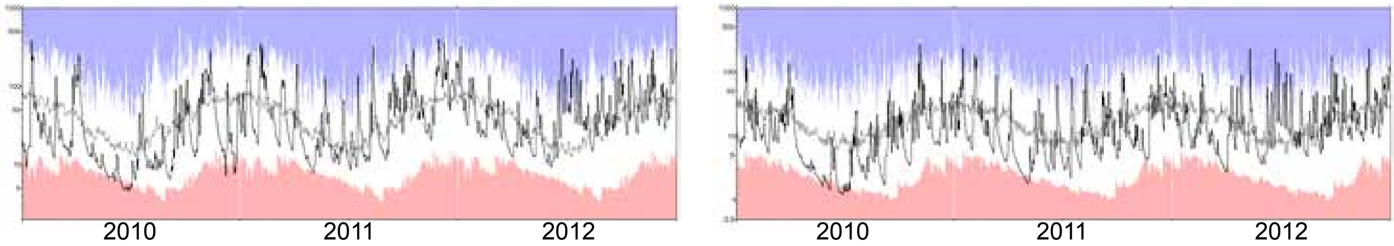
[h] Low flows were underestimated throughout the early record and, given the inaccuracies associated with war damage to Teddington weir in the 1940s, it is likely that the actual April-March runoff in 2011-12 was comparable with, or lower than that for 1943-44.

[i] Those in north-west Scotland excepted.

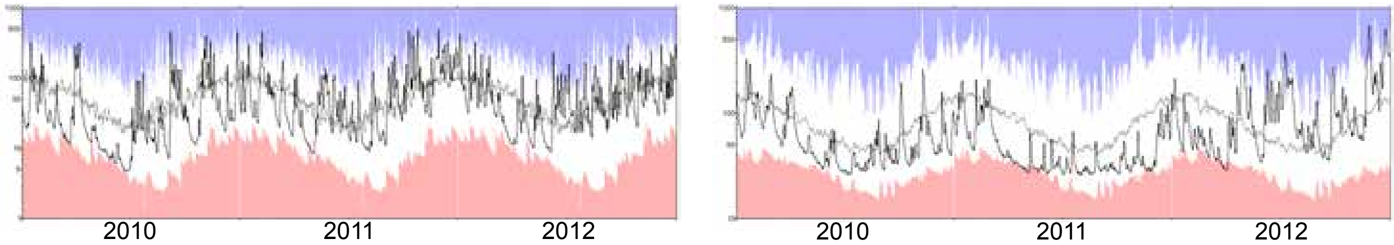
(a) Ewe at Poolewe	(b) Tay at Ballathie



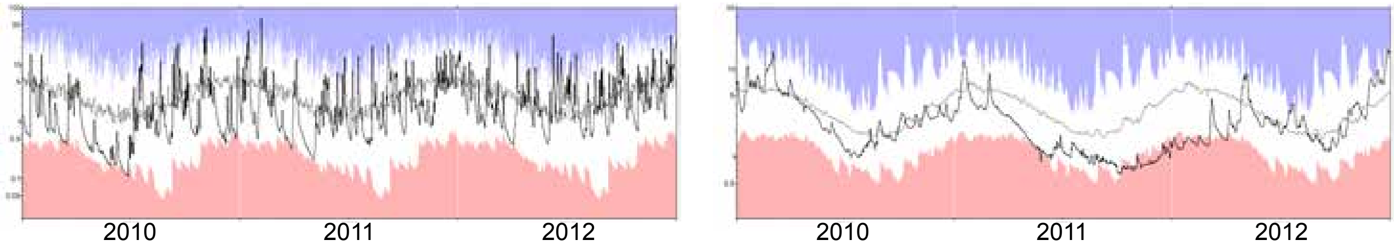
(c) Clyde at Blairston	(d) South Tyne at Haydon Bridge



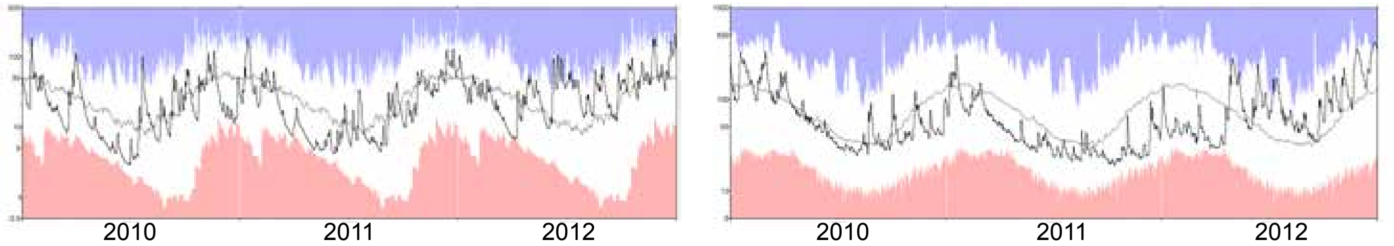
(e) Mourne at Drumnabuoy House	(f) Trent at Colwick



(g) Dee at New Inn	(h) Little Ouse at Abbey Heath



(i) Teifi at Glan Teifi	(j) Thames at Kingston



(k) Taw at Umberleigh	(l) Avon at Amesbury

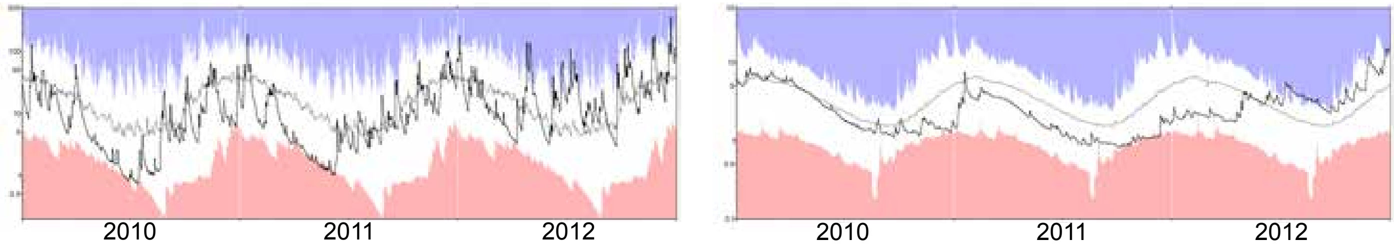


Figure 12 *River flows (m^3 s^{-1}) for 12 index catchments in the UK*

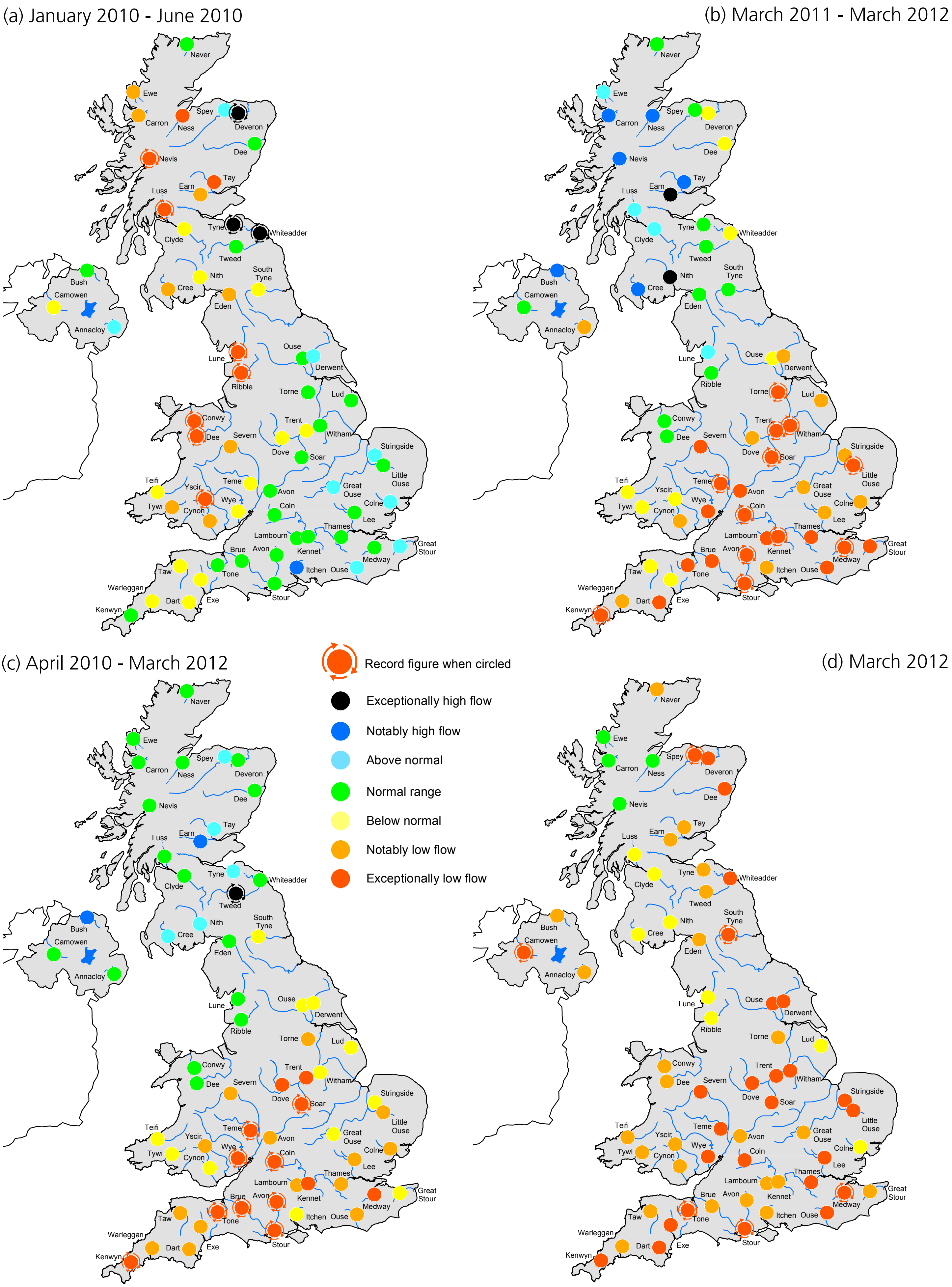


Figure 13 *River flow accumulation maps for selected periods during the 2010-12 drought*

Note: new period of record maxima and minima are circled

Table 5 *Maximum non-overlapping 24-month runoff deficiencies (1961-2012)*

** lta = percentage of 1971-2000 average*

(a) England & Wales

Rank	End Month	Runoff (mm)	% of lta*
1	Apr 1997	566	65.0
2	Jan 1977	629	71.6
3	Feb 1992	655	74.4
4	**Mar 2012**	**667**	**76.6**
5	Aug 1974	669	76.5
6	Nov 1965	680	77.6
7	Oct 2006	697	79.6
8	Feb 1963	701	79.8

(b) Lowland England

Rank	End Month	Runoff (mm)	% of lta*
1	Mar 1992	318	59.2
2	May 1997	324	60.2
3	**Apr 2012**	**338**	**63.0**
4	Oct 2006	371	68.7
5	Nov 1976	391	72.2
6	Aug 1974	394	73.2
7	Nov 1965	398	73.5
8	Feb 1963	414	77.0

(c) Teme at Knightsford Bridge

Rank	End Month	Runoff (mm)	% of lta*
1	**Mar 2012**	**418**	**55.7**
2	Aug 1976	427	57.1
3	Mar 1992	433	57.7
4	Apr 1997	477	63.7
5	Nov 2006	541	72.4
6	Oct 1990	584	78.0
7	Mar 2004	612	81.5
8	May 1985	708	94.6

(d) Trent at Colwick

Rank	End Month	Runoff (mm)	% of lta*
1	Apr 1997	386	55.2
2	**Mar 2012**	**441**	**63.0**
3	Nov 1976	450	63.8
4	Mar 1992	466	66.5
5	Nov 2006	535	77.0
6	Feb 1963	538	76.8
7	Aug 1974	567	81.4
8	Aug 1965	583	83.7

(e) Tone at Bishops Hull

Rank	End Month	Runoff (mm)	% of lta*
1	**Mar 2012**	**525**	**56.4**
2	Mar 1992	591	64.5
3	Sep 1976	637	68.6
4	Nov 1965	643	69.3
5	Apr 2005	671	72.1
6	Jun 1973	720	77.5
7	Feb 1963	735	79.0
8	Nov 1990	748	80.7

(f) Kennet at Theale

Rank	End Month	Runoff (mm)	% of lta*
1	Jun 1992	322	55.6
2	**May 2012**	**363**	**62.7**
3	Oct 2006	373	64.6
4	Dec 1997	384	65.6
5	Nov 1965	406	70.4
6	Jan 1977	420	72.0
7	Jul 1974	482	83.3
8	Dec 1989	525	89.7

(g) Kenwyn at Truro

Rank	End Month	Runoff (mm)	% of lta*
1	**Apr 2012**	**823**	**67.4**
2	Oct 2006	855	70.2
3	Mar 1992	893	72.9
4	Jan 1972	967	78.5
5	May 1997	978	80.1
6	Jan 1985	983	79.8
7	Mar 2009	1017	83.1
8	Nov 1976	1064	87.6

(h) Medway at Teston / East Farleigh

Rank	End Month	Runoff (mm)	% of lta*
1	Aug 2006	223	42.0
2	**Mar 2012**	**256**	**48.0**
3	Feb 1992	260	48.8
4	Apr 1973	322	60.4
5	May 1997	329	61.7
6	Feb 1963	346	64.8
7	Oct 2009	410	77.1
8	Dec 2004	417	77.6

that runoff deficiencies would continue to increase until well into the autumn, at least, across much of southern, central and eastern England.

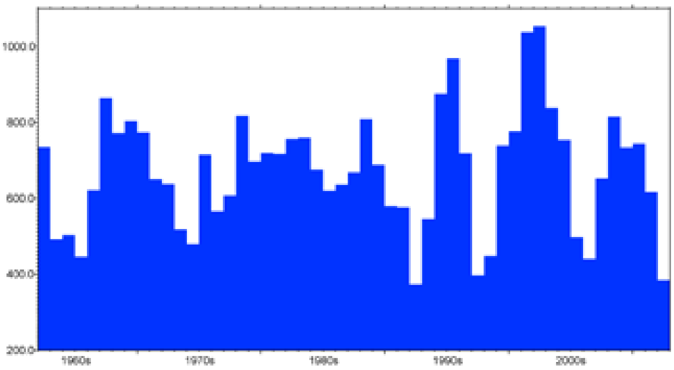


Figure 14 *Average two-year October-March outflows ($m^3 s^{-1}$) for Lowland England*

Table 6 *Rank of 2010-12 runoff minima for Lowland England across a range of timespans*

** lta = percentage of 1971-2000 average*

Months	Rank (/52)	2010-12 outflow ($m^3 s^{-1}$)	% of lta*	Start	End
6	4	181	53	Jun 2011	Nov 2011
12	2	239	47	Apr 2011	Mar 2012
18	4	299	58	Jun 2010	Nov 2011
24	3	316	62	May 2010	Apr 2012
30	5	370	72	Apr 2010	Sep 2012
36	4	384	75	Apr 2009	Mar 2012

Plate I *Upper Pang (Berkshire), April 2012*

Water resources

Water resources management in England & Wales incorporates a range of measures to augment water supplies and moderate demand as drought conditions intensify (see page 26).[12] The interconnectivity of water supply networks has increased substantially since the extreme drought of 1976, reinforcing the UK's resilience to even the most intense within-year rainfall deficiencies. However, the scope for regional and local transfers of water diminishes as the duration and spatial extent of drought conditions increase. Clusters of dry winters still present considerable water management challenges particularly in those regions where the margin between water supply and demand is modest.

Reservoir stocks

Monthly stocks for a network of UK reservoirs (and groups of reservoirs managed as a single resource) are given in Table 7 for a selection of months chosen to capture the seasonally exceptional range registered over the 2010-12 period.

Following abundant replenishment in November 2009 reservoir stocks were very healthy across almost the entire country but the water resources situation then deteriorated rapidly through the first six months of 2010, in western regions particularly. The March-June period saw the largest fall in overall reservoir stocks for England & Wales since 1995 and levels were particularly depressed in a number of smaller impoundments (see Plate II). In Scotland levels in Loch Katrine fell considerably below its previous June minimum in a series from 1994 (see Figure 15a). By late-June, the combined stocks for a network of major reservoirs in north-west England were at their

Plate II *Trentabank Reservoir (Peak District), June 2010*

Table 7 *Percentage live capacity and monthly anomalies for selected reservoirs*

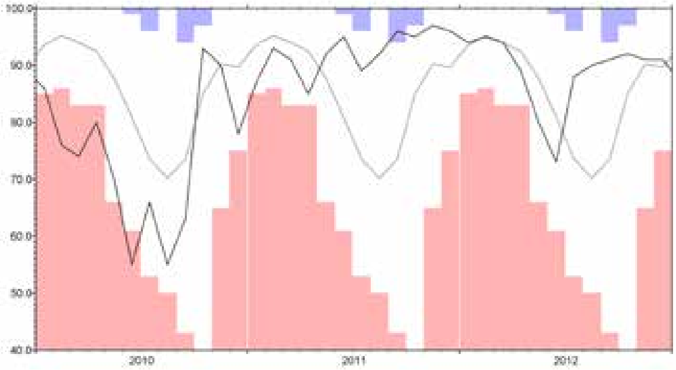
Area	Reservoir	Capacity (Ml)	2010 Jun	Jun Anom	2011 Nov	Nov Anom	2012 Mar	Mar Anom	2012 Jun	Jun Anom	Diff Mar-Jun 2012
North West	Northern Command Zone	124929	52	-21	81	4	84	-9	95	22	11
	Vyrnwy	55146	68	-15	80	-2	91	-4	99	16	8
Northumbria	Teesdale	87936	63	-16	90	10	92	-1	100	21	8
	Kielder Water	199175	84	-6	89	5	88	-4	99	9	11
Severn-Trent	Clywedog	44922	88	-6	88	8	99	4	98	4	-1
	Derwent Valley	39525	68	-13	72	-7	90	-5	100	19	10
Yorkshire	Washburn	22035	72	-9	86	13	96	3	96	15	0
	Bradford Supply	41407	65	-14	90	9	90	-4	99	20	9
Anglian	Grafham	55490	92	-1	82	0	96	5	96	3	0
	Rutland	116580	87	-1	63	-16	73	-18	98	10	25
Thames	London	202828	94	3	66	-16	97	3	98	7	1
	Farmoor	13822	95	-2	86	-4	100	5	98	1	-2
Southern	Bewl	28170	81	-1	35	-29	49	-41	91	9	42
	Ardingly	4685	93	-2	14	-61	51	-48	100	5	49
Wessex	Clatworthy	5364	70	-13	65	-13	92	-5	100	17	8
	Bristol	38666	77	-5	53	-15	80	-13	97	15	17
South West	Colliford	28540	88	6	51	-22	75	-11	83	1	8
	Roadford	34500	80	-2	58	-16	81	-4	89	7	8
	Wimbleball	21320	79	-7	49	-26	97	1	100	14	3
	Stithians	4967	79	0	50	-15	87	-6	95	16	8
Welsh	Celyn & Brenig	131155	83	-11	95	8	98	0	100	6	2
	Brianne	62140	82	-11	92	-4	91	-7	100	7	9
	Big Five	69762	70	-14	97	16	93	-3	100	16	7
	Elan Valley	99106	77	-12	100	6	93	-5	100	11	7
Scotland(E)	Edinburgh/ Mid Lothian	97639	81	-5	100	15	96	1	97	11	1
	East Lothian	10206	94	0	100	17	95	-4	100	6	5
Scotland(W)	Loch Katrine	111363	55	-26	97	7	94	0	73	-8	-21
	Daer	22412	74	-10	99	2	100	2	100	16	0
	Loch Thom	11840	82	-3	100	7	100	2	93	8	-7
Northern	Total	55540	73	-9	91	7	86	-2	96	14	10
Ireland	Silent Valley	20634	74	-3	91	14	84	0	100	23	16

Note: values represent end-of-month reservoir stocks. Monthly figures may be artificially low due to routine maintenance or water quality effects in feeder rivers.

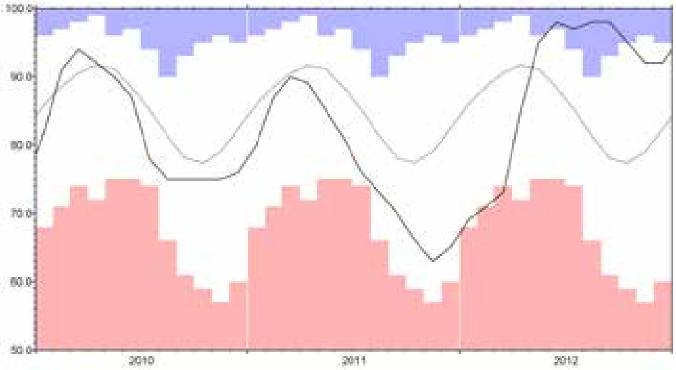
lowest for the time of year since the 1984 drought; this triggered the introduction of a temporary use ban (including a domestic hosepipe ban) affecting over six million people.[12] Fortunately, the exceptionally wet July ensured substantial inflow from the steep upland gathering grounds and most reservoir stocks recovered through the late summer and autumn. There were exceptions: in south-west Britain, Clatworthy registered its second lowest October level since the terminal phase of the 1995 drought. Late in 2010, the stress on water resources was locally exacerbated during the exceptionally cold December. Many reservoirs registered their largest November-December decline in stocks as frozen catchments greatly limited inflows and in Northern Ireland there were substantial water supply problems (see page 25).

Modest rainfall during the winter half-year of 2010/11 resulted in natural replenishment to a number of major lowland reservoirs in England being only around half of the long-term average and the spring of 2011 proved pivotal to the drought's development. Dry weather and high temperatures in March and April increased water demand[12] and accelerated the depletion of reservoir

(a) Loch Katrine (Trossachs)



(b) Rutland (East Anglia)



(c) Bewl (East Sussex)

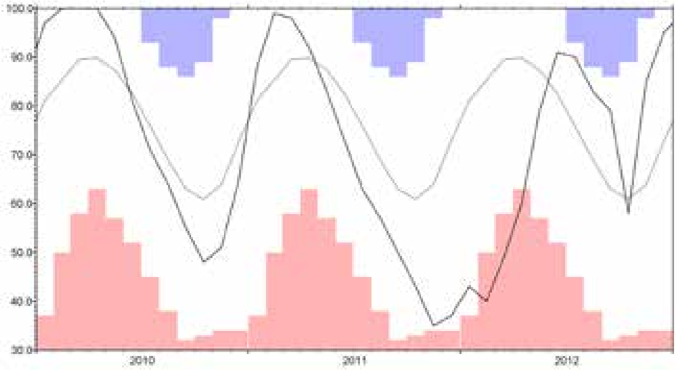


Figure 15 *Reservoir stocks (% of capacity)*

stocks. Notably low late spring reservoir levels were widely reported; in Wales, May stocks were the lowest since the 1995 drought in the Elan Valley reservoirs.[5] Across much of southern and central England (extending into south Yorkshire) water companies were increasingly drawing from alternative sources to help conserve reservoir stocks through the summer half-year. Nonetheless, stocks in gravity-fed reservoirs were generally well below the seasonal average by the summer; in Devon, stocks for early-July in Wimbleball reservoir equalled their lowest on record.

In most northern and western areas, stocks recovered through the late summer and autumn 2011 – by which time they were approaching, or exceeding, seasonal maxima in Scotland. In contrast, the depletion of stocks continued through the autumn of 2011 in the drought-affected regions. Late autumn stocks for Bewl reservoir were close to the lowest on record (see Figure 15c) and, in the Midlands, the Charnwood group of reservoirs fell below 40% of capacity by late-October.[5] Careful management of river abstractions and preferential drawing on groundwater sources helped maintain stocks in a number of large pumped storage reservoirs (including those servicing London's water needs – see Table 7) but, in December, stocks across much of southern England were seasonally depressed.

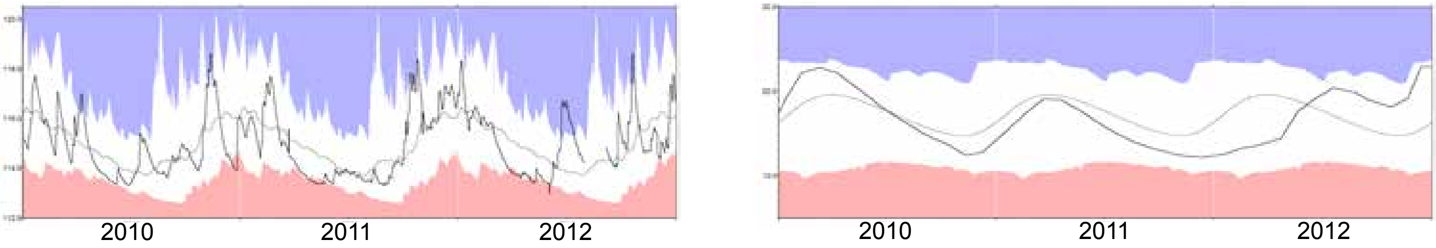
Generally, the recovery of stocks through the winter of 2011/12 was, again, weak; reservoir levels remained close to, or below, previous late winter minima across southern England and parts of the Midlands. March then saw the largest early spring decline in overall reservoir stocks for England & Wales since 1993. Early-April stocks were the lowest on record for a number of major reservoirs, including Rutland (Figure 15b), and stocks in a few southern impoundments (e.g. Bewl; Figure 15c) were only around 50% of capacity. Many farm reservoirs had also failed to fill through the winter and levels in a number of reservoirs servicing the canal network were also depressed. For example, reservoirs supplying the Oxford Union Canal remained below half of capacity and Naseby Reservoir, the primary feeder into the Grand Union Leicester Line, was at its lowest, for the beginning of the boating season, in a 20-year record[14].

Groundwater

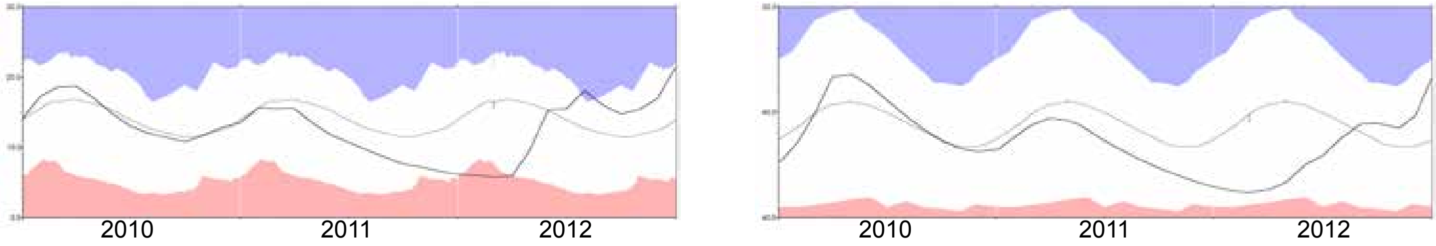
The amount of water stored in reservoirs across England & Wales is dwarfed by that stored naturally in aquifers and the abundance of groundwater resources normally provides an important buffer against drought stress. This is particularly true in eastern, central and southern parts of the UK – on average, the driest regions, and where groundwater, mainly from the Chalk aquifer, is a primary source of water supply. However, clusters of dry winters, with associated meagre recharge, can result in regionally depressed groundwater resources and dwindling flows in spring-fed streams and rivers. The characteristics of individual aquifer units, in particular their storage properties, vary greatly; this can be very influential in relation to the onset and decay of drought conditions.

Figure 16 illustrates groundwater level variability over the 2010-12 period for a selection of index wells and boreholes across the UK. As with reservoir stocks, groundwater resources were very healthy in late 2009. However, over the following two years, groundwater replenishment in most outcrop areas was greatly restricted due largely to the limited winter rainfall and exceptionally dry soil moisture conditions through the spring and autumn.

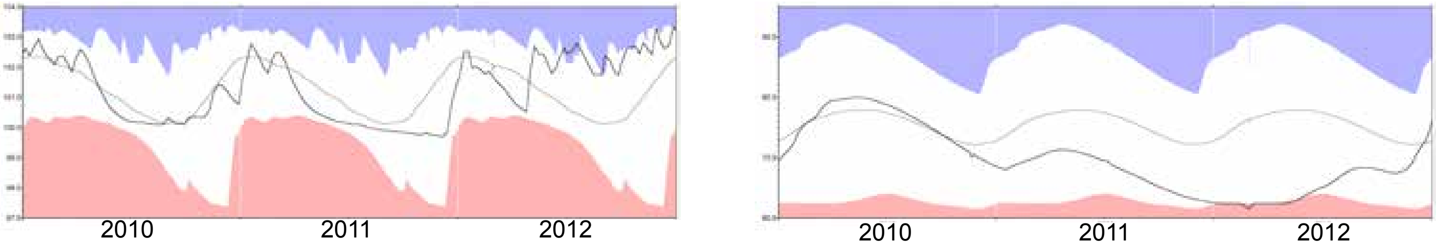
Groundwater levels through the first half of 2010 generally remained in the normal range but a very weak seasonal recovery in the autumn left levels notably low


(a) Killyglen (Chalk)

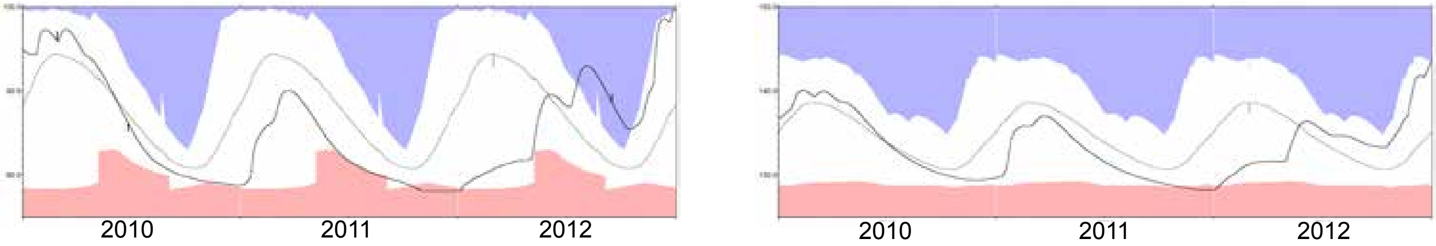
(b) Dalton Holme (Chalk)


(c) New Red Lion (Lincolnshire Limestone)

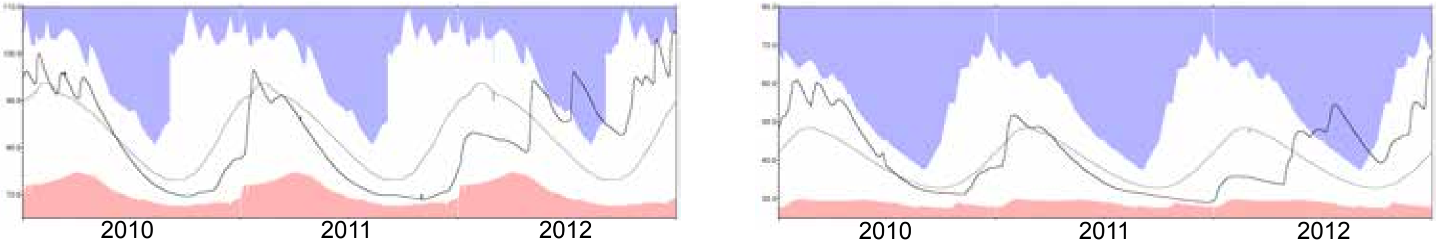
(d) Washpit Farm (Chalk)


(e) Ampney Crucis (Middle Jurassic Limestone)

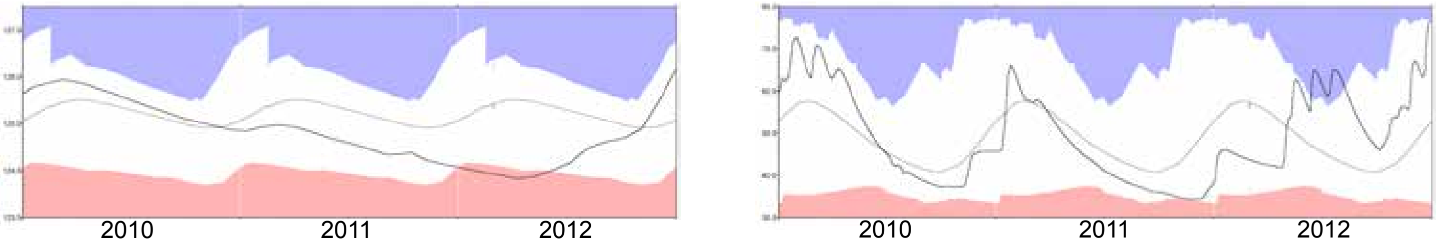
(f) Stonor Park (Chalk)


(g) Tilshead (Chalk)

(h) Rockley (Chalk)


(i) West Woodyates (Chalk)

(j) Compton House (Chalk)

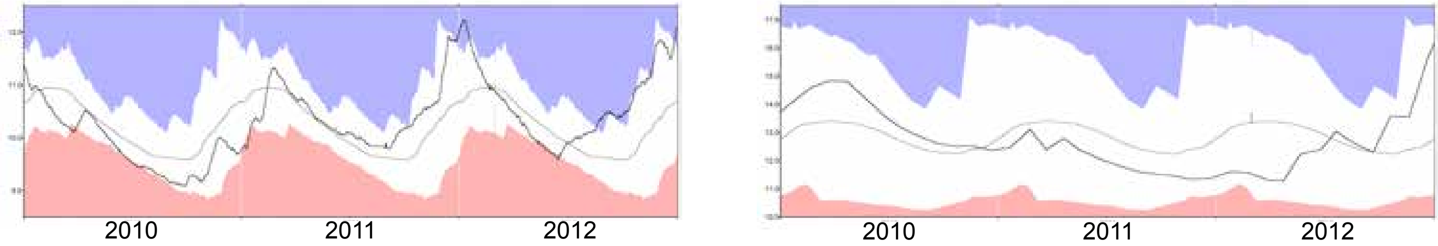

(k) Lime Kiln Way (Upper Greensand)

(l) Chilgrove House (Chalk)

Figure 16 *Groundwater levels (m aOD) for a selection of index boreholes in the UK*

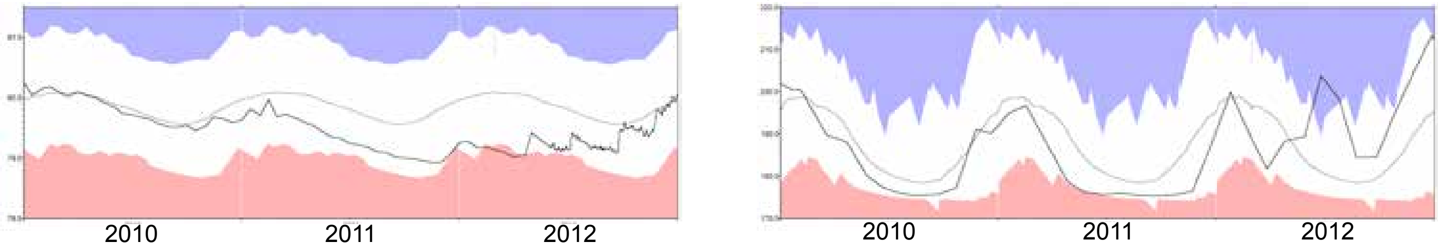
(m) Newbridge (Permo-Triassic sandstones)

(n) Brick House Farm (Magnesian Limestone)



(o) Llanfair DC (Permo-Triassic sandstones)

(p) Alstonfield (Carboniferous Limestone)



(q) Bussels No.7A (Permo-Triassic sandstones)

(r) Nuttalls Farm (Permo-Triassic sandstones)

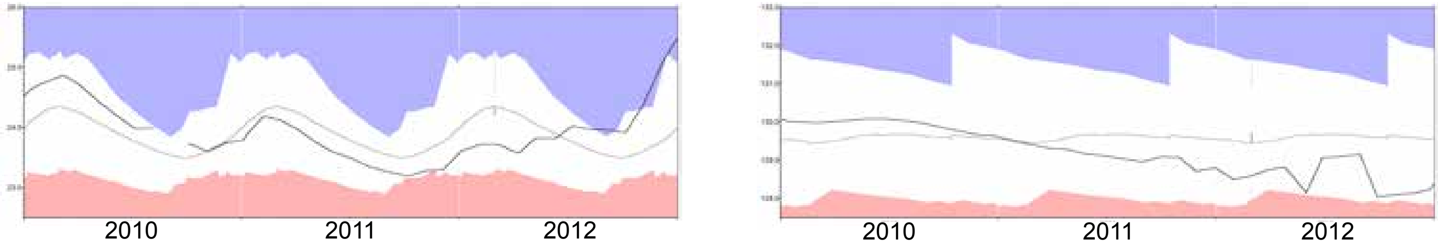


Figure 16 *(Contd.)*

in a few responsive northern aquifer units (e.g. in the Permo-Triassic sandstones of Dumfries and Galloway). Frozen ground conditions in December (which greatly restricted recharge opportunities) contributed to below average groundwater levels at year-end across the majority of aquifer outcrop areas.

Groundwater level recoveries through the winter of 2010/11 were spatially variable but relatively weak and recessions through the spring and summer of 2011 were both steep and protracted. Levels in the Carboniferous Limestone of Derbyshire (at Alstonfield) fell below previous May minima and, by July, water tables had fallen close to natural base levels[j] in a number of wells and boreholes in the southern Chalk. Late summer groundwater levels were also depressed in the slower-responding Permo-Triassic sandstones outcrops in the Midlands. The autumn then saw previous monthly minimum levels eclipsed in the western Chalk outcrop at Rockley (where records began in 1933) and very depressed levels in the Permo-Triassic sandstones of north Wales. Generally though, groundwater levels remained above the minima registered during the droughts of the 1990s and the mid-2000s.

The seasonally exceptional SMDs through the warm and dry autumn greatly delayed the onset of the 2011/12 recharge season. In October, the Tilshead borehole on Salisbury Plain went dry[k] for the first time since 1976 and the continuing fall in groundwater levels resulted in the failure of a number of private wells and boreholes (e.g. in Wiltshire and Shropshire[15]). Estimated recharge over the 2011/12 winter half-year fell below 20% of average over wide areas and groundwater level hydrographs for a number of boreholes in parts of the Chalk and Permo-Triassic sandstones outcrops showed no sign of any significant winter replenishment (see, for example, Figure 16f). Many winterbournes also remained dry.

Severity of the groundwater drought

In most aquifer outcrop areas, limited rainfall over the preceding winter half-year is a primary cause of depressed groundwater levels during the ensuing summer and autumn. However, the particular importance of antecedent winter rainfall over successive winters is evident when comparing 2012 with the remarkably intense drought of 1975-76[9]. Despite the driest October-March for England & Wales,

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[j] The point at which natural outflows via springs and seepages cease and groundwater levels stabilise.

[k] Groundwater levels having declined below the base of the well.

groundwater levels in the early spring of 1976 were less depressed than in 2012 across much of the central and eastern Chalk outcrop. This is primarily due to the very wet winter of 1974/75 which resulted in the 1975 groundwater level recessions beginning from notably high levels; the benefits of this were still evident a year later in the spring of 1976 (see Figure 17).

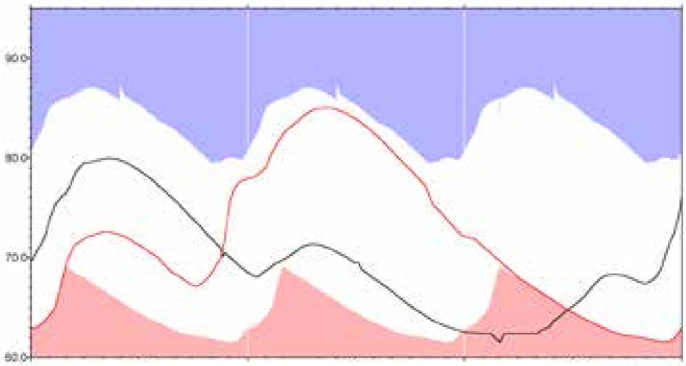

Figure 17 *Groundwater levels (m aOD) at Stonor Park (Oxfordshire), 1974-76 (red) and 2010-12 (black)*

Following very limited recharge in the winters of both 2010/11 and 2011/12, groundwater levels in March 2012 were exceptionally depressed, relative to the monthly average, in around 60% of index wells and boreholes across southern Britain (see Figure 18b); most reported new March minimum levels – in many cases in records extending over more than 40 years. Natural base levels had been reached, or closely approached, in many outcrop areas.

Over its full span the drought impacted particularly severely on the Chalk. Estimated overall storage in the Chalk, based on a network of seven index wells and boreholes with long records[l], was marginally lower than at the same time in 1976 and, in a series from 1942, only 1992 has registered modestly lower overall aquifer storage (see Figure 19).

The cluster of years with exceptionally depressed groundwater resources in the relatively recent past is atypical when considered in a broader historical context. Based on rainfall deficiencies for successive winter half-years, it is probable that groundwater levels at the climax of the 1995-97, 1990-92 and 2010-12 droughts were comparable with the greatest depletions in overall groundwater resources in the last 100 years. This is supported by observational evidence from a number of wells and boreholes in the Chalk with records extending back into the 19th century. In the South Downs, the Chilgrove House borehole has recorded March levels[m] below those of 2012 in only five years in a series from 1836, whilst at the Dalton Holme well, close to the northern limit of the Chalk, there were only four occurrences in the last 100 years. At Therfield Rectory[n] (Hertfordshire), the average March level in 2012 was the third lowest since 1946; however lower levels were regularly reported during the latter years of the 'Long Drought' which lasted from the late 1880s until 1908.[8] On the basis of the EWP winter rainfall figures it may be speculated that depleted early spring groundwater resources in the Chalk similar to those experienced in 2012 may also have occurred in the 1850s, 1829-31, 1789-91 and the early 1780s[o]. Interestingly, the relatively high frequency of extended periods with depressed groundwater levels over the last 40 years has occurred during a period when winter rainfall has, on average, been greater than that which typified the pre-1970 period.

The hydrological and water resources outlook in the early spring of 2012

The remarkably low soil moisture content across most of the country in the early spring of 2012 implied that, in the absence of extraordinary late spring and summer rainfall patterns, no sustained recovery in river flows or groundwater levels could be expected until the late autumn, at least, in most of the drought-afflicted regions.

Overall reservoir stocks and aquifer storage for England & Wales have been substantially more depressed than in the spring of 2012, e.g. during the droughts of 1990-92, 1995-97 and 2003. However, on these occasions the most depressed stocks occurred, as usual, in the late summer or autumn. Across central and southern England in 2012 early spring stocks in a number of major impoundments were close to the lowest on record at a time when groundwater resources were also exceptionally depleted. With no sign of a change in weather patterns in the drought-afflicted regions, the likelihood of sustained recoveries in reservoir stocks and groundwater levels was remote. Correspondingly, in early-April 2012, the water resources outlook across much of southern, central and eastern England was fragile.

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[l] The wells in this network are: Dalton Holme, Washpit Farm, Therfield Rectory, Compton House, Rockley, West Woodyates and Westdean – see Location Map.

[m] For most of the historical record only single groundwater levels are available for each month.

[n] Significant uncertainty is associated with the early groundwater level records for this well.

[o] The very limited rain gauge network in the 18th century implies considerable uncertainty in the national rainfall assessments.

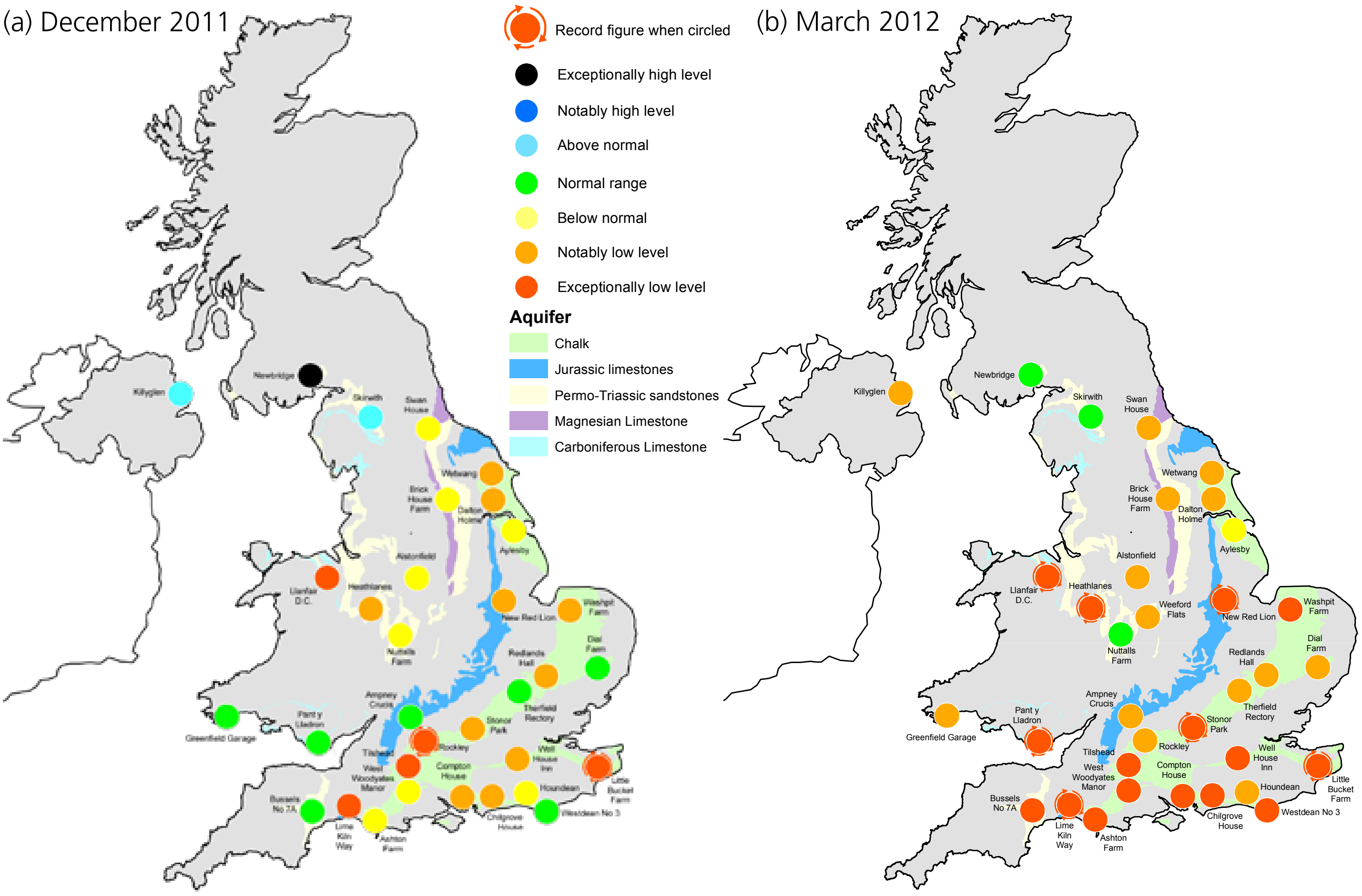


Figure 18 *Groundwater resources during the 2010-12 drought*

Note: new period of record maxima and minima are circled

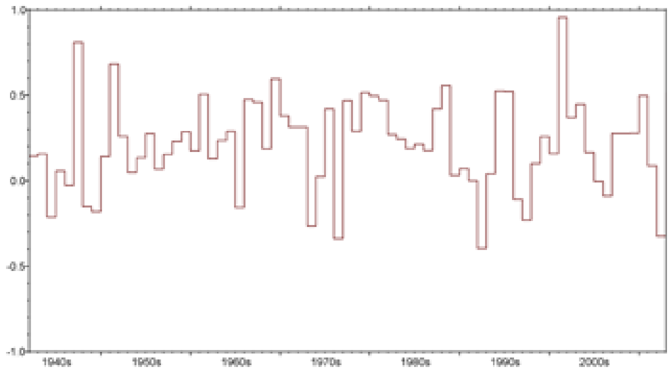


Figure 19 *Estimated average April groundwater stocks for the Chalk*

Drought impacts and mitigation measures

The impacts of the lack of rainfall over the 2010-12 period were widespread, sustained and multi-faceted reflecting the meteorological, agricultural, hydrological and ecological dimensions of the drought. The variations in the drought's intensity across the country, and throughout its duration, are also reflected in the contrasting severity of the impacts. For example, the seasonally exceptional soil moisture conditions were most severe across eastern England during the spring of 2011 (causing major problems for agriculture), whereas the drought's effect on groundwater was a cumulative process over successive winters contributing to substantial water resources stress in late 2011 and the spring of 2012. The ecological and environmental impacts were more focused on periods of seasonally depressed river flows and wetland water levels; these were often exacerbated by the limited dilution of effluents, low oxygen levels and the development of algal blooms – together resulting in considerable stress on aquatic wildlife.[1,12] Such circumstances also led to a loss of visual amenity and decreased opportunities for recreational activities.

In 2010 very dry spring soils caused concern for farmers, growers and gardeners, particularly in eastern England, and reports of heathland fires (for example in Surrey and Dorset[5]) began to increase. By June, reservoirs and lakes in western Britain were at seasonally very low levels and water use restrictions were introduced in north-west England (see page 20)[12]. Late summer and autumn rainfall greatly moderated the drought's impact but freezing conditions during December then created significant local water supply problems. In parts of Northern Ireland pipe bursts were a major contributory cause of inadequate stocks in a number of service reservoirs – water supplies to around 40,000 properties were affected; rota cuts were introduced, bowsers deployed and bottled water made available in a number of areas[5].

The drought's second phase, during the dry spring of 2011, also had adverse effects on agriculture and the environment, with eastern counties and the Midlands generally worst affected. The dry soils made it more difficult to prepare seed beds, triggered an early start to the irrigation season and affected the growth of both cereal and root crops; livestock farmers faced higher animal feed costs. Falling water levels in rivers and wetlands increasingly impacted on aquatic wildlife, in large part a consequence of habitat loss. Many rescues were undertaken as fish became stranded in isolated pools; overcrowding stress (with an associated enhanced risk of disease and parasitism) and predation rates also increased[12].

During the particularly parched conditions of the late spring and early summer outbreaks of forest, heathland and moorland fires were common affecting, for example, parts of Highland Scotland, Northern Ireland, mid-Wales, Lancashire and Berkshire. In Dorset significant damage to Upton Heath was reported in June[5]. During the summer, low flows, often accompanied by oxygen depletion, necessitated further fish rescues, e.g. in the Tarrant (Dorset) and Redlake (Shropshire); aeration equipment was also deployed (e.g. in the Hatfield Waste Drain near Doncaster[5]).

The agricultural stress eased during the summer of 2011 and the dry early autumn was beneficial in reducing the costs of drying grain. However the marked intensification of the drought through October and November resulted in renewed concern as farmers struggled to harvest crops from dry, hard ground; crop yields and quality were also affected[16], especially on light, sandy soils – shallow rooting crops (e.g. cereals, peas and linseed) suffered particularly badly.

As the drought became increasingly focussed on those parts of the country where water demand is generally highest, further measures to conserve, or augment, reservoir stocks were activated.[12] These included drawing on alternative or stand-by water sources (often groundwater), the greater use of local and regional water transfers, public appeals to moderate water demand, more vigilant leakage control and the use of Drought Orders to supplement existing stocks (e.g. by reducing river regulation releases). In London, Thames Water brought into operation the North London Artificial Recharge scheme and its desalination plant.[12]

In the latter stages of the drought, with little sign of any seasonal recovery in groundwater levels, the failure of springs and private wells increased; tankered supplies were required by consumers in some localities (e.g. in Shropshire and Dorset in the autumn of 2011[5]). Meagre aquifer replenishment resulted in many spring-fed ponds and streams drying up (see Plate I). Low flow augmentation schemes were widely deployed to help moderate the drought's ecological impact but continuing fish rescues were required.[5,12] Despite such mitigation measures, the exceptionally depressed early-April river flows were expected to herald substantial environmental and ecological stress through the summer of 2012.

Throughout the drought, the Environment Agency followed a pragmatic approach to licence regulation, allowing water to be taken outside of the designated winter season (e.g. to moderate impacts on stressed wetlands).[12] Nonetheless many farmers were unable to fill their reservoirs through the winter of 2011/12. During the early months of 2012, with restrictions on spray irrigation expected to be extended, some cropping patterns were revised in anticipation of a difficult growing season.[12] The irrigated crop sector faced a difficult spring and summer with a likelihood that available water would be exhausted before the planned harvest and an expectation that yield and quality would be poor (e.g. fruit and vegetables[16]). The limited amount of silage/foodstuff for livestock was also causing problems (and driving up food costs).

Many roads and parts of the rail network were affected by ground shrinkage[12]; Network Rail reported that the sustained lack of rain caused the track geometry to deteriorate to its worst levels since the 2003 drought.[17] At various times during 2010-12 stocks in a number of canal feeder reservoirs became heavily depleted. Temporary closures or movement restrictions in affected canal sections began in 2010 (for example on the Leeds & Liverpool Canal) and were more extensive later in the drought (e.g. on the Grand Union Canal and Oxford Canal[14]). Where practical, the Canal & River Trust augmented reservoirs stocks (e.g. using groundwater or pumping from alternative sources) and accelerated a programme of lock-gate relining to reduce leakage. Nonetheless, further restrictions on canal boat movement were introduced in March 2012 with the prospect of the most geographically widespread and severe restrictions across the network since the droughts of the mid-1990s.[14] Navigation was also restricted on a number of rivers (e.g. the Nene, where sluices were closed to conserve water upstream).

The sustained warmth and dry weather in late-March 2012 resulted in further, and seasonally early, moorland and heathland fires (e.g. in parts of south Wales, Surrey and the Scottish Borders[5]). On the 5th April, seven water companies imposed temporary use bans affecting 20 million consumers in eastern, central and southern England. Later in the month the area officially designated as 'in drought' was further extended to include counties in the West Midlands and south-west England. Hosepipe bans were inconvenient for many households and a few commercial customers suffered appreciable financial losses[12]. The prospect of further declines in seasonal runoff, reservoir stocks and groundwater levels through the summer of 2012, with all of the damaging attendant economic, social and environmental implications, seemed inevitable.

THE TRANSFORMATION – FROM DROUGHT TO FLOODS

Preamble

From early-April 2012 a sequence of very active Atlantic frontal systems heralded a protracted period dominated by cyclonic weather patterns, resulting in a notably wet late spring and summer across much of northern Europe[18]. Although punctuated by intervals of fine settled weather wet conditions continued across most of the UK until the end of the year. Hydrological droughts are rarely terminated by one or two wet months, especially during the summer half-year. In 2012 however, the record late spring and early summer rainfall provided a decisive termination to the drought conditions, rapidly shifting the focus of hydrological stress to flood risk, and heralding a remarkable episode of very sustained high runoff across most parts of the UK.

An appreciable number of abrupt terminations to droughts in the UK may be indentified in the historical record (see pages 39 and 40). However, a defining characteristic of 2012, especially in a hydrological context, was the drought's termination through the late spring and summer when, particularly in those parts of England and Wales where drought conditions were most severe, high evaporation demands and dry soils conditions normally mitigate against any sustained hydrological recoveries. In 2012 the seasonally extreme early-April soil moisture deficits across much of the UK were dramatically eliminated and soils were close to saturation at month-end across much of the country. As a consequence, the runoff response to the extreme late spring and early summer rainfall was more typical of a wet winter. Correspondingly floodplain inundations became increasingly widespread and sustained, and runoff rates were seasonally outstanding throughout much of June and July. After a relatively quiescent August, river flows remained exceptionally high throughout much of the remainder of 2012, culminating in two major runoff episodes in late-November and late-December.

To help emphasise the extraordinary nature of the runoff and recharge patterns in 2012, the following hydrometeorological commentaries are presented within two timeframes: the first (April-July) focuses on the drought's terminal phase; the second (August-December) reviews the rainfall and flooding which characterised much of the autumn and early winter. In some sections a supplementary review of 2012 as a whole is also included.

Rainfall

April-July 2012

After a dry start to April, the Jet Stream adopted a persistent southerly track (Figure 20) and the associated westerly airflow brought successive pulses of heavy rainfall across most of the country. This synoptic pattern remained dominant throughout the remainder of a year in which many existing national, regional and local rainfall records were eclipsed. Areal rainfall statistics for selected periods during the hydrological transformation are presented in Table 8; the rainfall distribution is mapped in Figure 21.

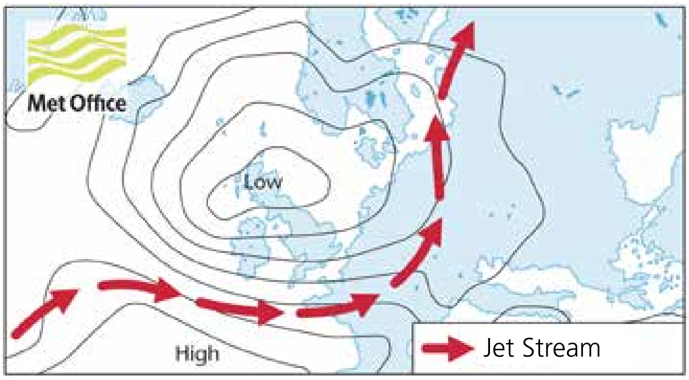


Figure 20 *Predominant path of the Jet Stream during the 2012 transformation*

April was the wettest in the EWP series with rainfall totals approaching four times the average in a few localities. The cool, unsettled weather conditions continued well into May, but rainfall totals were mostly near average for the month overall. June, however, replicated April by exceeding the previous monthly maximum for England & Wales. Locally, there were several extremely wet interludes: on the 8th/9th a 48-hour rainfall total of 186 mm was recorded at Dinas reservoir (central Wales); on the 22nd Honister (in the Lake District) reported a rain day total of 208 mm; and on the 28th short period rainfall rates equivalent to over 50 mm an hour were reported[19] (other exceptional rainfall events are listed in Table 9). Generally however it was the persistent spells of heavy rain that contributed most to the extreme April-June rainfall. For England & Wales, it was the wettest April-June period by a margin equivalent to an additional month's rainfall.

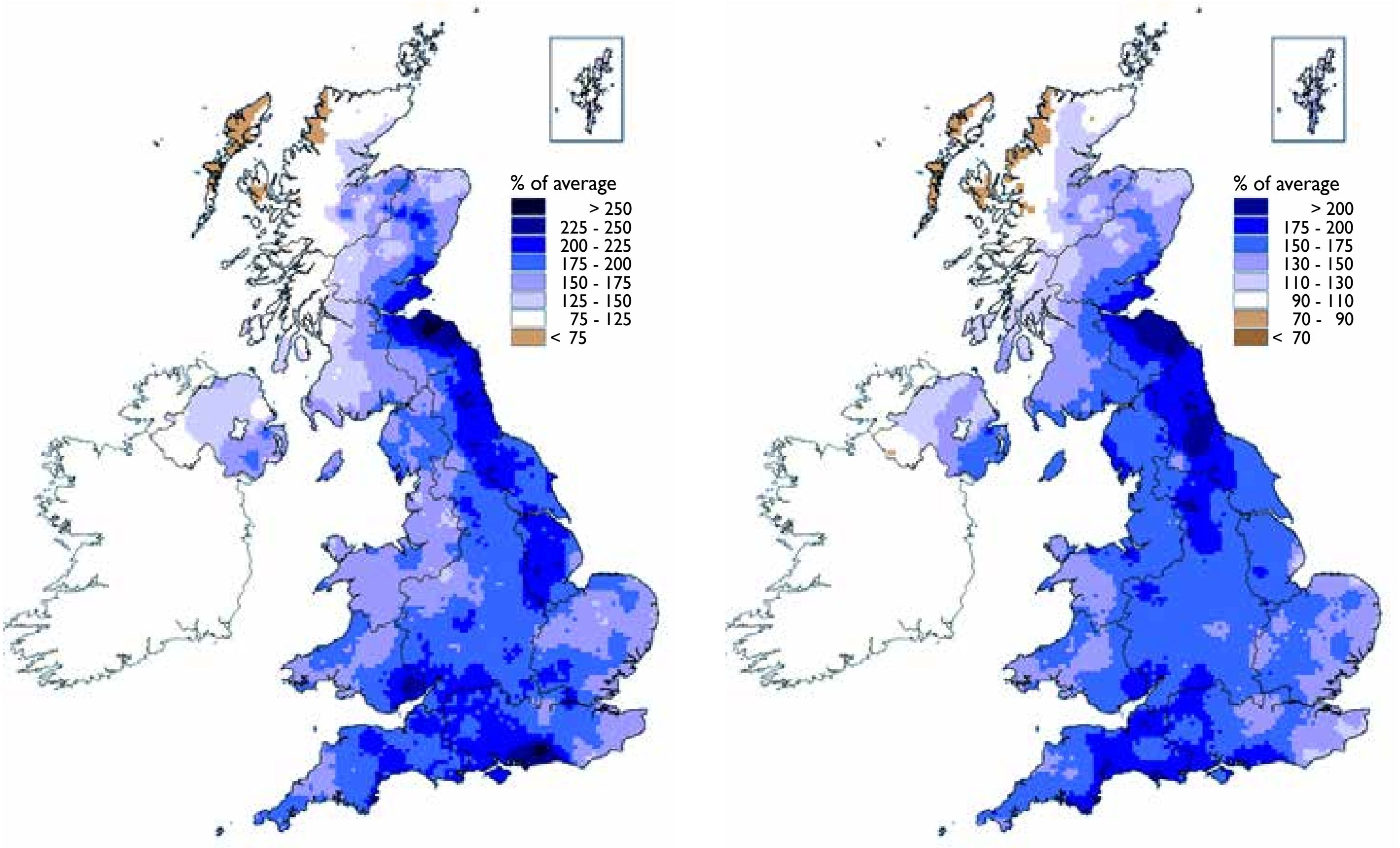
Cyclonic conditions continued through the first two-thirds of July with exceptional 48-hour rainfall totals over the 6th and 7th in east Devon[20] – a number of raingauges registered >100 mm. For the month as

Table 8 *National and regional rainfall totals and associated return periods for selected durations during 2012*

Area	**Rainfall**	**Apr 2012**	**Jun 2012**	**Apr12 - Jul12**		**Apr12 - Sep12**		**Apr12 - Dec12**		**Nov12 - Dec12**	
					RP		*RP*		*RP*		*RP*
United Kingdom	mm	128	149	462		686		1126		314	
	%	193	215	174	>>100	155	>>100	143	>>100	134	10-20
England	mm	137	148	452		630		1009		271	
	%	247	240	202	>>100	175	>>100	165	>>100	159	20-30
Scotland	mm	114	126	449		732		1251		367	
	%	142	160	141	20-35	133	15-25	122	15-25	114	2-5
Wales	mm	169	219	598		886		1492		457	
	%	209	267	191	>>100	167	>100	150	>>100	144	10-20
Northern Ireland	mm	70	179	416		640		966		205	
	%	98	252	146	15-25	136	20-30	119	8-12	90	2-5
England & Wales	mm	141	158	472		666		1076		297	
	%	240	245	200	>>100	173	>>100	162	>>100	156	20-30
North West	mm	108	202	536		868		1371		361	
	%	161	259	185	>>100	178	>>100	158	>>100	141	10-15
Northumbria	mm	139	162	498		738		1115		278	
	%	236	268	211	>>100	196	>>100	179	>>100	164	40-60
Midlands	mm	141	148	453		621		942		245	
	%	258	238	206	>>100	178	>>100	165	>>100	162	15-25
Yorkshire	mm	153	150	464		678		1048		279	
	%	262	239	203	>>100	187	>>100	172	>>100	166	25-40
Anglian	mm	121	108	377		473		740		183	
	%	266	198	198	>>100	159	>100	158	>>100	162	15-25
Thames	mm	132	138	411		522		852		222	
	%	259	245	202	>>100	162	>100	160	>>100	160	10-20
Southern	mm	130	134	414		535		912		245	
	%	250	241	205	>>100	164	>100	156	>100	143	5-10
Wessex	mm	156	157	482		664		1120		329	
	%	279	261	220	>>100	184	>>100	176	>>100	175	30-50
South West	mm	184	183	550		795		1425		460	
	%	257	253	201	>>100	174	>100	165	>>100	163	25-40
Highland	mm	119	86	403		711		1269		393	
	%	128	96	113	2-5	114	2-5	105	2-5	98	2-5
North East	mm	169	113	448		614		962		236	
	%	263	172	173	>100	147	20-30	136	20-30	124	2-5
Tay	mm	125	132	476		705		1184		336	
	%	186	191	168	40-60	147	15-25	134	15-25	124	2-5
Forth	mm	107	148	507		753		1203		320	
	%	172	213	189	>>100	165	>100	148	>100	135	8-12
Tweed	mm	115	181	550		807		1232		288	
	%	192	279	216	>>100	197	>>100	175	>>100	146	10-20
Solway	mm	82	216	533		883		1464		412	
	%	102	275	166	>100	160	>100	144	>100	133	5-10
Clyde	mm	88	163	491		843		1489		462	
	%	97	183	134	8-12	128	8-12	121	10-20	121	5-10

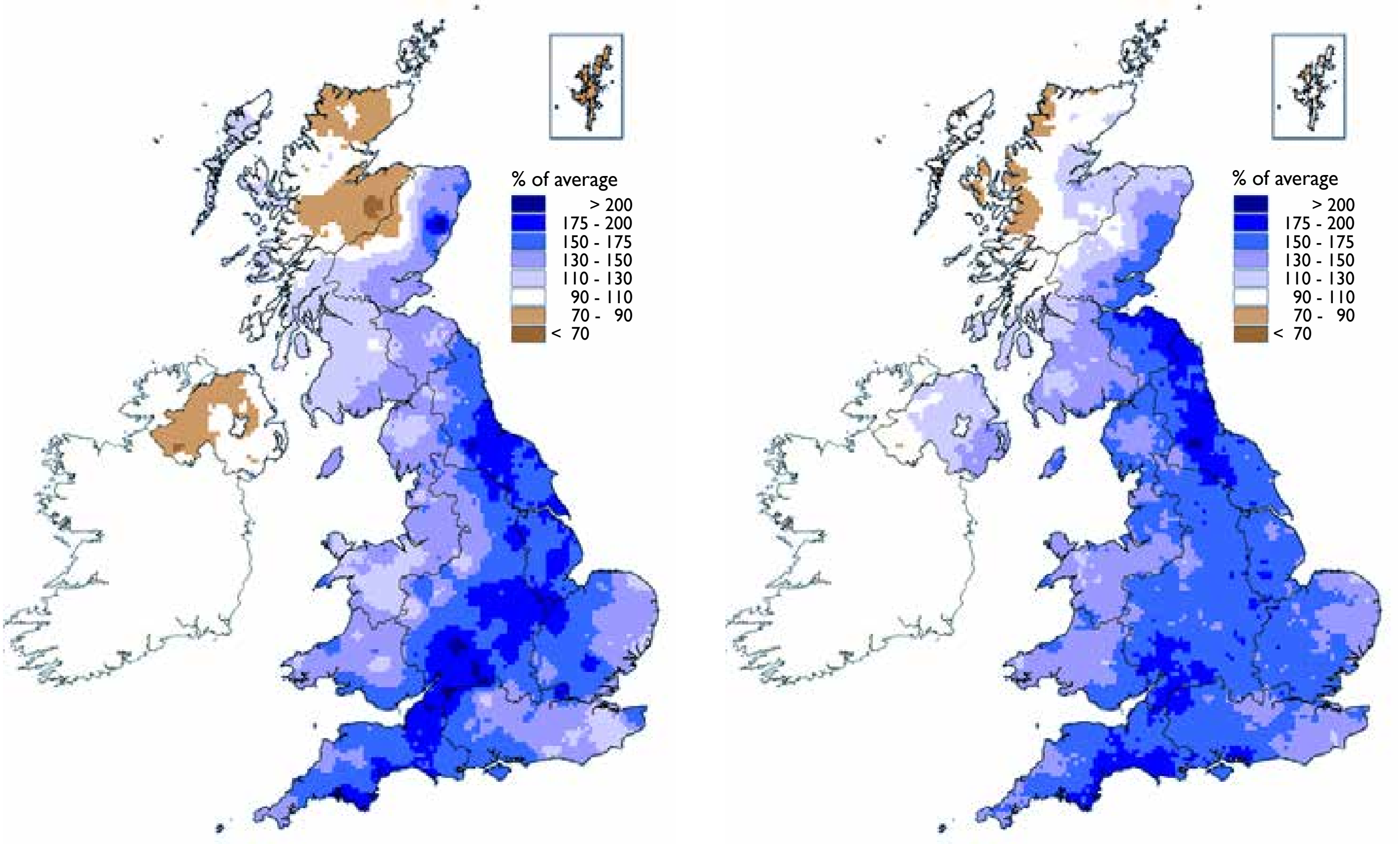
% = percentage of 1971-2000 average *RP* = return period

Note: the return period estimates are based on data provided by the Met Office and reflect climatic variability since 1910; they also assume a stable climate. 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 details of methodology used see reference Tabony (1977)[2]



(a) April 2012 - June 2012

(b) April 2012 - September 2012



(c) November 2012 - December 2012

(d) April 2012 - December 2012

Figure 21 *Rainfall anomaly maps (% of 1971-2000 average) for selected accumulation periods during the 2012 transformation*

Table 9 *A selection of notable rainfall totals*

Note: unless otherwise stated, dates refer to rain days

Date	Location	Rainfall total (mm)
13th May	Kinlochewe (Highlands)	101
7th June	Treherbert (S Wales)	105
8th - 9th June	Dinas Reservoir (Rheidol)	186
10th June	Chilgrove House	101
10th - 11th June	Bognor Regis	145
21st - 22nd June	Arncliffe (N Yorks)	121
22nd June	Honister Pass (Cumbria)	208
6th - 7th July	Charminster (Dorset)	132
6th - 7th July (12-hour)	Upper Don and Calder	60
23rd - 25th September	Richmond (N Yorks)	144
24th September	Dungonnell Filters (NI)	147
19th - 25th November	Holne (Devon)	273

a whole, many parts of England, Wales and southern Scotland received more than twice the average rainfall. As a result, the April-July rainfall was almost twice the average, easily exceeding the total for the previous seven months. Rainfall records were also broken for many long-running individual rain gauges – for example, at Oxford, April 2012 was the wettest and June the second wettest in a series from 1767.[21]

The drier exception through much of this period was the far north-west of Scotland where, in an often easterly airflow, the area was largely unaffected by many of the low pressure systems further south. Western fringes also tended to benefit from a reversal of the normal west-east rain-shadow effect. For the Western Isles, the March-July rainfall total in 2012 was the second lowest in 40 years and significant drought stress was experienced through the summer and early autumn.

August-December 2012

In most regions, August was the driest month of the summer; nonetheless most areas again registered above average rainfall, south-west England was particularly wet, and the summer (June-August) was the UK's wettest since 1912. Weather patterns remained mostly unsettled through the autumn of 2012. In September, heavy rainfall associated with a deep low pressure system – a remnant of hurricane 'Nadine' – formed part of a rapid succession of heavy rainfall events contributing to one of the wettest weeks across England & Wales in the last 50 years. England recorded its wettest autumn since 2000 with outstanding rainfall totals in parts of the south-west and north-east, reflecting the tracks of the low pressure systems and associated rain-bearing fronts.

The weather for the first half of December was generally quieter and relatively dry until the 14th when many areas recorded rainfall totals of 20-30 mm heralding a further very wet episode. Cumulative rainfall totals for the five days beginning on the 20th were particularly impressive, including a three-day total for Stonehaven (Aberdeenshire) of 169 mm. Taken together, November and December were the second wettest for England & Wales since 1929.

Notwithstanding the extreme rainfall recorded in a number of localities during the April-December period, the transformation was generally more dependent on the high frequency of storm totals in the 10-30 mm range. Table 10 ranks the annual frequency of daily rainfall totals ≥10 mm for the Centre for Ecology & Hydrology's Meteorological Station; notwithstanding the dryness of the first three months, the number of days in 2012 with rainfall exceeding the threshold was the highest in a series from 1962; by contrast the highest daily rainfall in 2012 ranks fifth lowest in the daily maxima series. (The truly exceptional accumulation of rainfall over the April-December period is examined on page 39.)

Table 10 *Rainfall statistics for the Centre for Ecology & Hydrology's Meteorological Station (Wallingford)*

Year	Number of days >10 mm rainfall	Annual maximum daily rainfall	Rank of annual maximum in a 51-year series (1=highest)
2012	**27**	**22.6**	**47**
2002	21	27.6	34
2000	20	40.2	12
2007	19	48.8	6
1966	18	28.7	32
1974	18	36.0	16
1982	18	26.0	41
1985	18	30.4	24
1992	18	52.3	4
2008	18	26.1	40

Temperatures, evaporation and soil moisture

Following well above average temperatures for much of the first three months of 2012, there were brief spells of warmth during the summer half-year of 2012 but otherwise cool conditions predominated with some unusually cold episodes. April and June were both the coolest such months for over 20 years but summer (June-August) temperatures overall were near to the 1971-2000 average for the UK.

The extreme rainfall, modest temperatures and high humidity levels moderated evaporation losses. Potential evaporation losses were notably low for England & Wales in June and July but otherwise remained within the normal range throughout the April-December period in 2012. In contrast, actual evaporation (AE) losses were largely unconstrained by dry soil conditions from late-April and, the May-September AE losses for England & Wales were considerably above average, ranking eighth highest in a series from 1961.

The characteristic seasonal cycle in soil moisture content was barely recognisable through the summer half-year in 2012 (see Figure 8). A remarkably rapid wetting-up of soils in April was followed by very erratic variations in SMDs but no sustained development of soil moisture deficiency that normally characterises the summer months. The near-saturated soils facilitated extreme rates of summer infiltration and the recommencement of aquifer recharge at a time of very depressed groundwater levels.

River flows

Having registered new minimum outflows from the UK for early-April, runoff rates climbed steeply across most of the country and outflows from both England and Wales exceeded the previous maximum for the final week of the month (see Figures 11a and 11c). Seasonally outstanding river flows ensured that the hydrological drought was effectively terminated by July[p] and, with flows remaining close to, or above, bankfull for lengthy periods, accumulated runoff totals over a range of timespans were outstanding (see Figure 22). Correspondingly, flood risk remained high into the early winter of 2012/13.

April-July 2012

In impermeable catchments across most of northern and western Britain runoff rates increased rapidly through April and, by the final week, flood alerts were widespread, affecting rivers from Cornwall to north-east Scotland. In May, with outflows from many springs and seepages increasing smartly, monthly runoff totals were also outstanding for rivers with significant groundwater components; the Bedford Ouse exceeded its previous maximum May runoff in a series from 1933.

June outflows from Great Britain exceeded the previous maximum by a wide margin and flood warnings were again very widespread from early in the month (there were >50 Flood Warnings on the 6th/7th across England & Wales). In Wales, the Rheidol exceeded its previous maximum flow, by a wide margin and new maximum recorded flows were reported for other rivers in Wales and north-west England (see Table 11 for a selection of exceptional flows in 2012). Floodplain inundations were particularly common across a large swathe of the UK from south-east Scotland to Devon, and in Northern Ireland where estimated outflows exceeded the previous June maximum in a series from 1981. However, whilst peak flows were seasonally very exceptional they were often exceeded later in the year.

Heavy rainfall in early-July triggered a further spate of flood alerts and there were also many incidents of pluvial flooding. Some localities reported multiple flood episodes through late-June and early-July, e.g. in Calderdale (West Yorkshire) and parts of Dorset where groundwater flooding become a contributory factor.[5] Many rivers registered mean July flows five, or more, times the monthly average and runoff over the April-July period was the highest on record for around 70% of index rivers in England & Wales (and a majority in southern Scotland also; see Figure 22a). It is likely that across much of the country the extent of summer floodplain inundations, as opposed to the number of properties flooded (see page 34), has no close modern precedent.

In contrast, drought conditions persisted in north-west Scotland where the Ewe reported its lowest July mean flow and second lowest April-July runoff in a 42-year record.

August-December 2012

After briefly returning to the normal seasonal flow range in mid-August, runoff rates increased again and the geographical spread of catchments subject to floodplain inundations through the summer as a whole was remarkable. The Environment Agency reported that over 4,000 properties in England & Wales had suffered fluvial or flash flooding by the end of August; this figure would have been substantially higher in the absence of flood protection measures.

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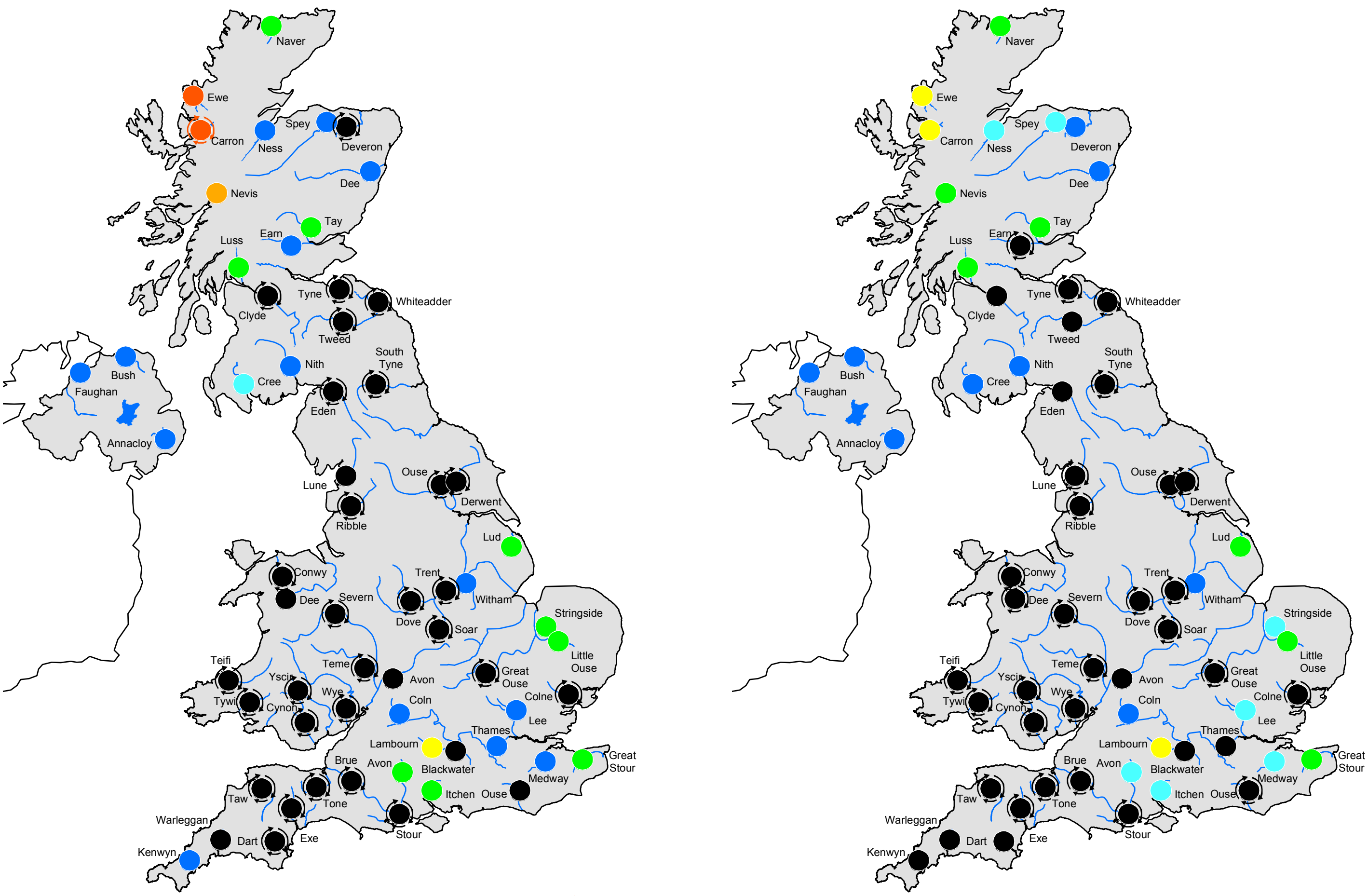
[p] Note however that groundwater levels remained depressed in some slow-responding aquifers until much later in the year.


(a) April 2012 - July 2012

(b) April 2012 - September 2012

(c) November 2012 - December 2012

(d) April 2012 - December 2012

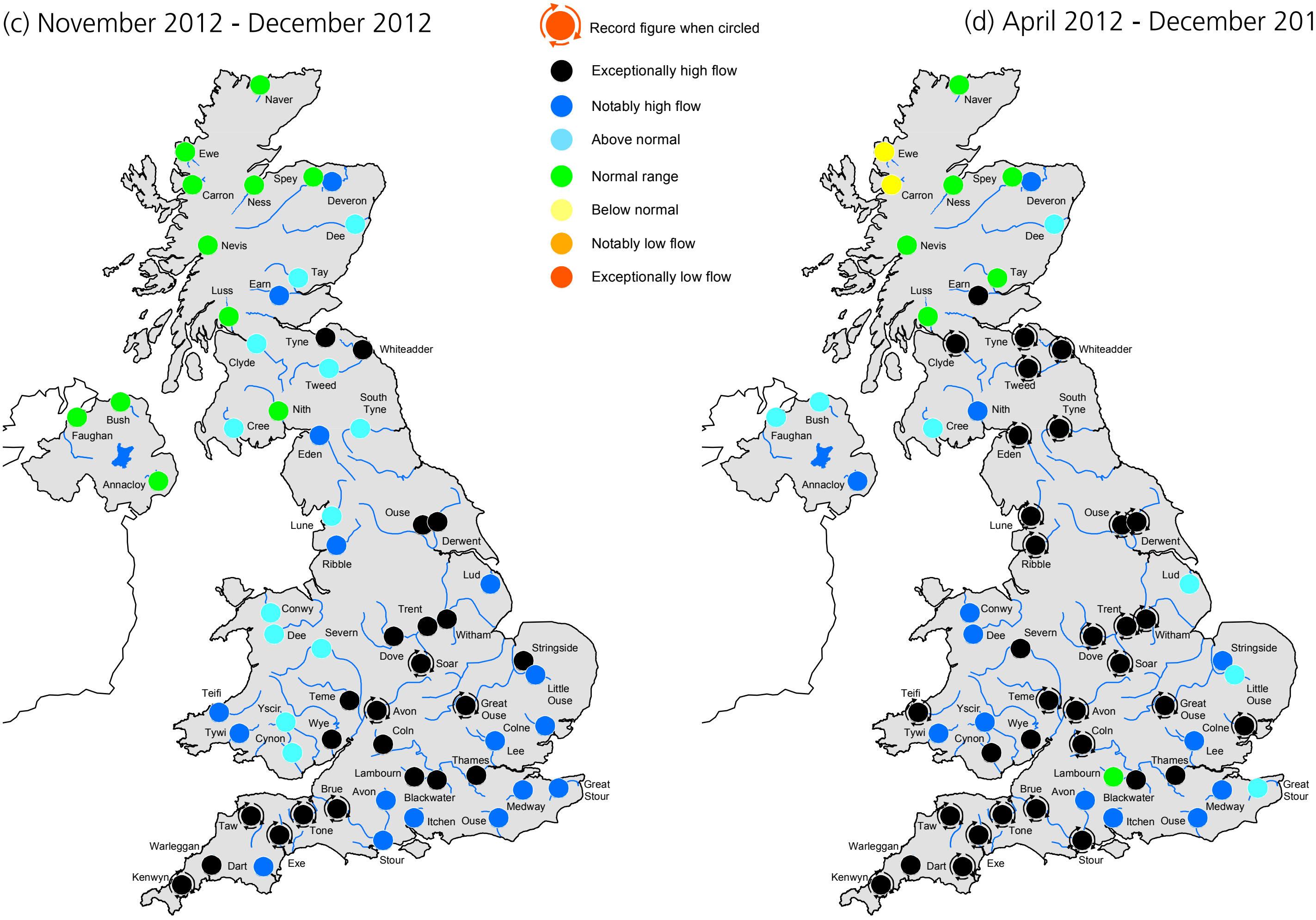


Figure 22 *River flow accumulation maps for selected periods during the 2012 transformation*

Note: new period of record maxima and minima are circled

Table 11 *Maximum flows in 2012 with associated return periods^*

Note: annual maxima are subject to future revision

River Name	**Station Name**	**Catchment Area**	**Date of Peak (in 2012)**	**Flow (m³ s⁻¹)**	**Estimated Return Period (years)**
Ythan	Ellon	523	23rd Dec	109.1	15-20
Bervie	Inverbervie	123	22nd Dec	106.2	>50
Blackadder Watr	Mouth Bridge	159	25th Sep	99.5	15-20
Coquet	Rothbury	346	25th Sep	285	15-20
Ouse	Skelton	3315	26th Sep	521	35-45
Calder	Elland	341.9	22nd Sep	295	15-20
Trent	Drakelow Park	3072	26th Nov	357	>50
Anker	Polesworth	368	25th Nov	127	>50
Bedford Ouse	Roxton	1666	28th Nov	137	20-25
Coln	Bibury	106.7	25th Dec	6.56	40-50
Dour	Crabble Mill	49.5	14th Jul	3.15	20-25*
Sydling Water	Sydling St Nicholas	12.4	7th Jul	1.81	35-45
Exe	Thorverton	600.9	22nd Dec	316	20-35
Exe	Pixton	159.7	22nd Dec	121	>50
Sherston Avon	Fosseway	89.7	24th Nov	18.2	>50
Ogmore	Bridgend	158	22nd Dec	208	>50
Rheidol	Llanbadarn Fawr	182.1	9th Jun	323	>50
Clwyd	Pont-y-Cambwll	404	27th Nov	94	40-45
Irwell	Bury Ground	139.9	22nd Jun	179	40-50
Calder	Whalley Weir	316	22nd Jun	330	25-30
Agivey	Whitehill	100.5	22nd Jun	94.6	8-12

^ Return periods estimated using methods based on the Flood Estimation Handbook (Institute of Hydrology, 1999. Flood Estimation Handbook, 5 vols. with associated software. NERC.) and historic data from the HiFlows-UK dataset: http://www.environment-agency.gov.uk/hiflows/91727.aspx

** The Dour is a chalk stream but with substantial urban development in the lower catchment; return periods for such rivers need to be treated with particular caution.*

Flows at the beginning of autumn were seasonally typical but towards the end of September outflows from England & Wales again exceeded the previous maxima for the time of year. These exceptional early autumn flows contributed to summer half-year runoff totals which exceeded the previous maxima for England & Wales by >30%. Flood Alerts continued into October but a drier spell in early-November witnessed the longest sequence of below average daily outflows since the early spring. However, runoff rates again increased dramatically during the fourth week; by the 26th, nearly 300 Flood Warnings were in operation embracing all regions of England & Wales – a rare circumstance. Exceptional flows were widely reported with sustained and damaging floodplain inundations (e.g. in north Wales, see page 38); large tracts of agricultural land remained under water and, with leaves and other debris hindering urban and rural drainage, flash flooding incidents were also common.

The above pattern was repeated prior to Christmas with pluvial, fluvial and groundwater flooding incidents again extensively reported, causing widespread transport disruption and major damage in some localities: the Environment Agency reported that 570 properties were flooded between the 15th December and year-end. Rivers with peak flows exceeding previous maxima extended from eastern Scotland to south-west England. Generalising, the initial flooding occurred in smaller, rapidly-responding catchments, with the most destructive flood episodes in south-west England (e.g. Braunton in north Devon). In Scotland, on the 22nd/23rd around 100 properties were evacuated at Stonehaven (Aberdeenshire) by which time most major rivers across the country (including the Thames, Severn and Trent) were above bankfull, remaining so for extended periods.[5] In Yorkshire, the Foss floodplain was inundated for six weeks[22]; a contributory factor was an exceptionally high baseflow contribution from the headwaters. Spring flows in southern aquifer outcrop areas were also outstanding and incidents of groundwater flooding were increasingly common. For England & Wales as a whole, late-December outflows exceeded previous maxima by a notable margin and, in the last 50 years at least, only in October/November 2000 have higher 10-15 day outflows been registered at the national scale.

Flooding in 2012

Runoff patterns through the last nine months of 2012 served to heavily underline the importance of floodplains as natural conduits for excess runoff and, given that runoff in the May-December timeframe from England & Wales exceeded the previous maximum by an appreciable margin, it is surprising that only around 8,000 properties were affected by the 2012 flooding. This reflects a number of factors. The fortuitous dry interludes in May and July (and later in the year) moderated flood risk at crucial times. In addition, the more even distribution of the exceptional rainfall, compared, for example, to the summers of 2007 and 1968, generally meant that floodplains, whilst often inundated, were less frequently confronted with runoff volumes that typify extreme events in individual river basins. Crucially, the limited property damage is also a testament to the effectiveness of the expanding network of flood defences across the country; in England & Wales these are estimated to have protected around 200,000 properties.[12]

Water resources

Reservoir stocks

April-July 2012

Reservoir stocks are normally at a maximum in the early spring and thence decline through the summer and, in the driest regions, much of the autumn. In 2012, the remarkable April runoff increased stocks in many northern and western reservoirs to well above the normal spring range and, counter to the normal seasonal pattern, reservoir stocks for most gravity-fed impoundments in England & Wales continued to increase through much of the summer. Restrictions on water use and preferential drawing from alternative water supply sources in some drought-stressed areas made moderate contributions to the recoveries in reservoir stocks but the extreme rainfall was the decisive factor.

Overall reservoir stocks for England & Wales rose modestly through May and then substantially through June. Recoveries in some eastern, central and southern parts of England were less rapid than in most upland impoundments in the north and west. Nonetheless stocks in virtually all index reservoirs exceeded the seasonal average by mid-summer (see Table 7). In some drought-afflicted regions the water resources recoveries were particularly remarkable. Rutland registered its greatest two-month increase in stocks in a series from 1988 (see Figure 15b) and eclipsed both monthly minima (in March) and maxima (in May) during the spring of 2012. By the end of July stocks in almost all index reservoirs across the UK exceeded 90% of capacity and most farm reservoirs were full. However, stocks in a few reservoirs in north-west Scotland remained well below the seasonal average.

August-December 2012

August generally witnessed modest declines in reservoir stocks but recoveries then gathered further momentum through the autumn. In September a number of reservoirs were spilling including Naseby (Northamptonshire) and the much larger Caban Coch in central Wales – see Plate III). The exceptional rarity of the water resources recovery in 2012 is underlined by the fact that average overall stocks for England & Wales through the summer half-year (April-September) were greater than all the winter half-year averages in the national series – which begins in 1989. Across the drought-afflicted regions many reservoirs registered their largest six-month increase in stocks on record. Stocks generally declined slightly in October but the exceptional November and December rainfall necessitated some drawdown of upland reservoirs to help moderate downstream flood risk.

Plate III *Caban Coch reservoir (central Wales), 26th September 2012*

In a number of lowland impoundments (depending wholly or partly on pumped storage from rivers) stocks fell substantially through the autumn of 2012 due to high turbidity and nitrate levels and other water quality problems limiting the periods over which abstraction was possible. A particular issue for a number of water companies was the exceptionally high levels of metaldehyde (which is a constituent of slug pellets[q])[23]. Expensive modifications to existing treatment processes would have been required to reduce metaldehyde concentrations. Correspondingly, abstraction management techniques were employed

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[q] These were widely used by farmers in 2012, particularly on oilseed rape.

(e.g. by Anglian Water) to minimise water quality risks and this action resulted in some reservoir levels remaining below the seasonal average. For example, at Grafham – which has a small natural catchment – stocks were below 75% of capacity at year-end. Refill opportunities were maximised as soon as metaldehyde levels reduced and healthy storage levels were achieved by early 2013.[23] Estimated overall stocks for major impoundments across Lowland England were above 95% of capacity in January 2013 and, elsewhere, stocks were generally at, or very close to, capacity.

Groundwater

In a normal summer high evaporative demands and dry soil conditions severely restrict aquifer recharge. Substantial groundwater replenishment has occurred episodically during especially wet summers (e.g. in 1968 and 2007) but 2012 witnessed substantial and sustained recharge throughout much of the late spring and summer. As a consequence groundwater level hydrographs for many index boreholes exhibited major departures from the normal seasonal pattern: minimum groundwater levels were registered early in the year followed by a maximum in the summer or early autumn. Differences in local rainfall patterns, the depth to the depressed water tables and particularly the storage characteristics of individual aquifer units did, however, make for marked differences in the time of onset of recharge and the rate of groundwater level recoveries.

April-July 2012

In early-April groundwater levels were seasonally depressed over wide areas (Figure 16). By month-end however, the fastest-responding wells and boreholes (generally in fractured aquifers) had registered substantial groundwater level increases; e.g. in the Cotswolds and in some parts of the southern Chalk. In south Wales, an increase of four metres in 24 hours (April 29th/30th) was reported for a borehole in the Carboniferous Limestone. In many central and eastern areas however, the primary function of the April rainfall was to eradicate SMDs and allow percolation to become re-established.

Infiltration rates during May were considerably lower than in late-April but still seasonally exceptional. Aided by the lagged water table responses to the April deluges groundwater levels rose very substantially – by more than ten metres at Chilgrove House (West Sussex) – and recoveries were evident in all but the slowest-responding aquifer units. In the latter category, Heathlanes (in the Permo-Triassic sandstones of the Midlands) reported its lowest May level in a series from 1972 (see Figure 23).

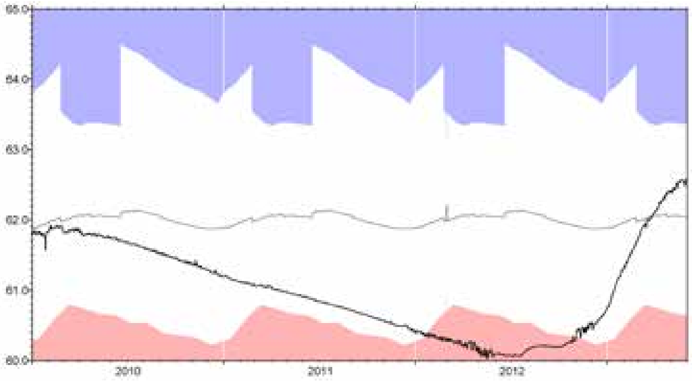

Figure 23 *Groundwater levels (m aOD) at Heathlanes, January 2010 - May 2013*

The record June rainfall, together with a substantial volume of recharge descending through the unsaturated zone, made for remarkable early summer increases in groundwater levels. During June, levels in the Carboniferous Limestone at Alstonfield (Derbyshire) rose 14 metres to exceed the previous monthly maximum by a wide margin. Levels in some boreholes tapping the western Permo-Triassic sandstones outcrops and the fissured southern Chalk also approached, or exceeded, monthly maxima. In Northern Ireland, levels in the Chalk at Killyglen closely matched the minimum for June early in the month and, subsequently, exceeded the maximum by an appreciable margin.

Locally intense downpours during the first week of July contributed to further sharp increases in groundwater levels – at Kingston Russell (Dorset) levels in the Chalk rose 12 metres in three days. By month-end, levels in index wells throughout the limestone outcrops and much of the southern and western Chalk were seasonally outstanding (Figure 24a). In a few areas (e.g. Winterbourne Abbas in Dorset) local, and rare, instances of summer groundwater flooding were reported. However, groundwater levels remained depressed in parts of the slowest-responding Chalk outcrops (e.g. in the Chilterns) and, particularly, in the Permo-Triassic sandstones of the Midlands where high storage capacities result in characteristically sluggish groundwater level recoveries.

August-December 2012

Aside from the slowest-responding aquifer units, groundwater levels for the late summer of 2012 were generally above normal late winter levels. Index wells and boreholes registering new maximum August groundwater levels were very widely distributed (from Scotland to Dorset) and, more notably, average summer levels were the highest on record for more than half of the index wells and boreholes in England & Wales. At Tilshead (on Salisbury Plain), where groundwater levels entering 2012 were comparable with the minima registered in 1976, mean levels in July, August and

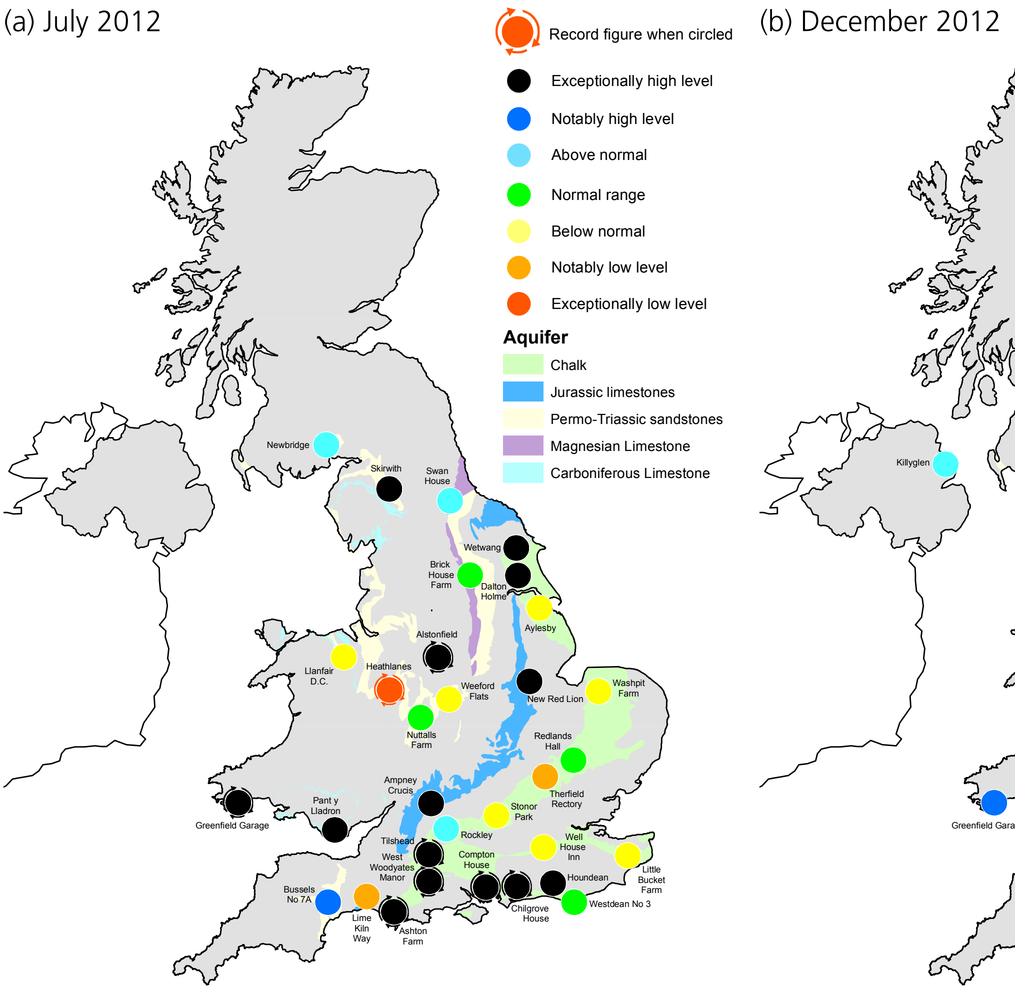

Figure 24 *Groundwater resources during the 2012 transformation*

Note: new period of record maxima and minima are circled

September all equalled, or exceeded, previous monthly maxima.

The early autumn saw groundwater levels fall in a number of areas, particularly across the limestone outcrops, but abundant recharge in November and December left groundwater levels in most index wells and boreholes close to, or above, previous end-of-year maxima (see Figure 24b). Levels at Rockley in the western Chalk outcrop exceeded the previous December maximum in an 80-year series and flows in many spring-fed rivers and streams were close to, or above, bankfull; outflows from upland springs which rarely sustain flows were widely reported (see Plate IV). End-of-year flows in the Ewelme Brook (Oxfordshire) were, with the exception of 2000, the highest in a series from 1970. The risk of groundwater flooding in vulnerable areas remained high well into 2013, although actual groundwater flood events were limited to relatively few areas, mainly in Berkshire and Dorset where persistently high groundwater levels caused localised flooding and sewer backflow[r]. Underlining

Plate IV *The Ewelme Brook sustained by spring outflows high in the Chilterns, March 2013*

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[r] A contributory factor to the limited groundwater flooding in 2013 is thought to be the very depressed groundwater levels in the early spring of 2012 - these allowed more scope for groundwater to drain freely from recharge areas.

the complexity of groundwater response following the prolonged drought conditions, some boreholes in the Permo-Triassic sandstones of the Midlands remained dry entering 2013 and, at Heathlanes, average monthly levels were not reached until April 2013 (Figure 23).

Impacts of the transformation

The sustained and heavy April rainfall in 2012 was initially welcomed by farmers and growers and, with the eradication of the extreme early spring SMDs, the agricultural drought could be considered to have terminated by early-May. The record rainfall also brought an unexpected and dramatic improvement in water resources. Most of the hosepipe bans were lifted in mid-June and the remaining restrictions on water use were withdrawn in July.[12] However, as the extreme weather conditions continued they had increasingly adverse impacts on agriculture, transport, ecology and leisure pursuits and, most directly, on areas vulnerable to flooding.

From late-April, the near-saturated soils and associated waterlogging restricted access to land and the use of farm machinery. An estimated 5,000 hectares of farmland was flooded[16], restricting grazing opportunities and often necessitating the movement of livestock away from pasture at risk. Large tracts of agricultural grassland were submerged for many weeks with a serious loss of grazing opportunities and winter feed – the Somerset Levels were particularly badly affected.[24] The sustained flooding caused erosion and structural damage to soils and the loss of beneficial invertebrates (worms in particular), and an associated reduction in crop yields. Supplementary feed had to be provided to livestock many of which needed to be housed because of the wet conditions. The impact of the reduction in fodder yields and availability continued into 2013.[16] The intense downpours increased soil erosion and resulted in additional leaching of nutrients from the soil. There were particular concerns in mid-Wales regarding potential contamination of agricultural land with harmful heavy metal pollutants eroded from the spoil heaps of abandoned mines.[25]

Ground conditions, together with the difficulties in applying herbicides and pesticides, and the outbreak of fungal infections (e.g. in potatoes), contributed to a significant reduction in crop yields. For example, there was a 14% reduction in wheat yield relative to 2011 (despite a slightly increased acreage planted) and a 7.3% decline for oilseed rape despite a major increase in acreage following favourable planting conditions in 2011.[26] Farmers generally reported reduced and poorer quality crops, with some – including cauliflower, carrots and cabbage – rotting in the fields. Production costs were increased across much of the agricultural sector and supermarkets were forced to accept sub-standard produce. The cool weather and low light levels hampered the development of soft fruit and garden centres reported very poor sales. The unseasonable weather also affected consumer purchasing habits (reducing demand for salad vegetables for example) whilst contractual arrangements restricted the ability of farmers and growers to switch to alternative crops.[16] The National Farmers Union estimated in December that the cost to rural Britain of the exceptionally wet weather in 2012 had run to £1.3 billion.[27]

The persistently wet weather and associated flooding had serious infrastructure consequences. Surface water, together with mud and debris washed off adjacent hillslopes, closed a number of motorways. In remote areas, road closures caused substantial diversions, and hundreds of people were rescued from cars stranded in floodwaters. The rail network fared little better, with tracks subject to landslides of unstable waterlogged ground; in late-June 2012, both the West Coast and East Coast mainlines to Scotland were blocked by landslips. More substantial landslides, some causing considerable structural damage (e.g. in Whitby) or endangering walkers (e.g. along parts of the Jurassic Coast in Dorset) were reported by the late summer.[28] On the 24th July a fatality occurred at Burton Bradstock following a major rockfall[s]. Road and rail transport disruption was severe and extensive through much of the summer, and again late in the year. In December, floodwaters eroded railway embankments leaving tracks suspended in mid-air; such an event occurred just north of Exeter, rendering the south-west inaccessible by rail in the busy run-up to Christmas.[12] Water transport also suffered: ferries were cancelled and navigation became dangerous on some rivers. In September a bank collapsed (due to the saturated ground conditions) at Dutton on the Trent & Mersey Canal, resulting in a seven-month closure.[29]

Many of the flood incidents in 2012 were localised in nature and caused by intense local downpours (rainfall rates often exceeded 20 mm per hour) overwhelming local drainage systems rather than triggering extensive fluvial flooding.[5] In late-June, the Tyne and Wear Metro in Newcastle was inoperative due to flooded tunnels and collapsed walls, and flights arriving at Birmingham airport were diverted. Such flash flooding formed an important component of the hydrological transformation during 2012 but the extent and duration of floodplain inundations in the April-July timeframe was seasonally remarkable. A few of the major flood events necessitated evacuations, e.g. in Wales (on the 9th June) when the Rheidol and Ystwyth overtopped their banks[30]; more than 1,000 people required temporary accommodation. Fluvial flooding was again

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[s] Probably triggered by a combination of factors: heavy rainfall, coastal erosion, stress release and long-term weathering; thermal expansion may also have played a part[28].

severe in north-east England during September (e.g. at Morpeth and Stockton) and further damaging flash flooding affected many localities (e.g. at Chew Magna, Somerset). In October, on the 10th/11th, a flash flood in a steep-sided coastal catchment caused significant damage in Clovelly (north Devon) and in the following month, major floodplain inundations necessitated the evacuation of modern housing estates in Ruthin and St. Asaph (north Wales).[5] December witnessed further exceptionally sustained floodplain inundations, extending beyond a month in parts of the Vale of York and Oxfordshire for example. There was also a substantial increase in the number of reported incidents of groundwater flooding.[12]

Floodplain inundations and rising water levels had mostly adverse ecological effects. Although initially beneficial, the continuing rise of water levels in wetlands and nature reserves destroyed nests of ground-nesting birds (e.g. in the Ouse Washes[12]) and restricted visitor access to flooded areas.[31] With a few reserves remaining under water for ten weeks or more (e.g. in south Oxfordshire), the associated invertebrate mortality restricted feeding options for a range of predators. Partridges suffered particularly in the wet conditions – fewer eggs hatched and the chicks struggled to find insects to sustain them; many bird species saw a reduction in the numbers of chicks fledged. The recession of floodwaters often stranded fish populations on floodplains, necessitating major fish rescues (e.g. on the Severn in Worcestershire during May[12]). Calls to pest control specialists doubled as rats were flushed out from flooded sewer systems, and part of the annual swan census in Sunbury-on-Thames, Surrey was cancelled, perhaps for the first time in its 900-year history. Nevertheless, a number of wading birds may have benefitted from moist ground once the floodwaters receded, and some butterfly species from the abundance of grass. Generally, however, butterfly populations suffered badly through the wet summer; 13 species experienced their worst year on record since scientific monitoring began in 1976.[32]

The frequency of storms combined with waterlogged conditions throughout the summer months led to a significant impact on leisure activities. Some indoor attractions benefited from increased visitor numbers but outdoor events, and tourism generally, were badly hit. In June, thousands of festival-goers on the Isle of Wight were forced to spend the night in cars after fields used as car parks turned into mud-baths, and the Great Yorkshire Show, costing £2.2 million to stage, was cancelled. Many sporting events were postponed or cancelled across the country, including rugby, cricket, tennis, golf, horse racing and swimming fixtures; the Badminton Horse Trials were cancelled for only the second time in their history, and grand prix car enthusiasts were encouraged not to attend practice sessions at a waterlogged Silverstone. High river levels marooned narrowboats near Tewkesbury on their way to the Queen's Diamond Jubilee Pageant on 2nd-4th June (the 3rd was very wet and cold, several people required treatment for hypothermia). The Olympic torch relay continued on in spite of bad weather; fortunately the Olympics (late-July to mid-August) and Paralympics (late-August to early-September) coincided with a fair amount of fine weather. Throughout much of the holiday period many caravan parks remained vulnerable to the repeated floodplain inundations (e.g. those beside the Nene and Great Ouse in East Anglia).

Whilst much of England & Wales experienced record rainfall, in parts of northern and western Scotland drought conditions continued. There were reports of exceptionally low river flows[5], springs drying up[t] and depressed loch levels; as a consequence whisky production was interrupted (e.g. on Mull and Islay), and wildfires were also common (one threatened historic buildings in Stornoway[34]).

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[t] For example, at the end of June, the rain gauge observer at Tornapress, Ross-shire reported their local spring running dry.[33]

HOW RARE WAS THE TRANSFORMATION EXPERIENCED IN 2012?

The UK has a rich legacy of hydrometeorological datasets, extending back more than 300 years, allowing the 2010-12 drought and subsequent hydrological transformation to be viewed in a very long historical context. The rarity of the transformation in 2012 is considered here with a focus on the contrasts between the first three months of the year and the late spring and early summer.

Rainfall

The exceptionally wet summers of 1879 and 2007, and the contrasting summers of 1911 and 1912[35] serve as reminders that extreme weather patterns occurred in the past as they do today. Rapid terminations of drought conditions are also not that unusual. Recent examples include 1984 and, most exceptionally, 1976[9] when the driest 16 months on record for England & Wales was followed by the fourth wettest autumn in a series from 1910. The contrast between the summer and autumn rainfall in 1976 is unique in the entire period for which instrumented rainfall data are available.

In the context of the 2012 transformation, it is the particular seasonal focus of the dry and wet episodes that sets 2012 apart. For England & Wales, rainfall over the April-June period was two and a half times that for the preceding three months. Such a contrast to the normal seasonal pattern over the first six months of the year has not been approached since 1830 (see Figure 25[u]) and, coming at a critical time for water resources, it was truly transformative.

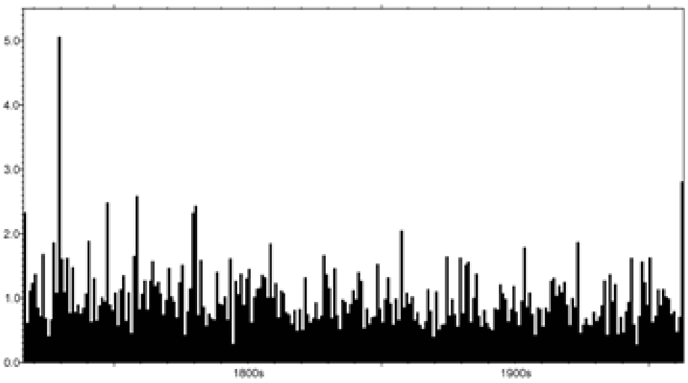

Figure 25 *Ratio between April-June and the preceding January-March rainfall in the England & Wales Precipitation series*

July was also notably wet and the summer half-year (April-September) for England & Wales was the third wettest on record – although notably wet summer half-years were more common in the late 18th and early 19th centuries. November and December in 2012 were also exceptionally wet, contributing to a rainfall total over the last nine months of 2012 that eclipsed the previous maximum April-December total in the EWP series by a clear margin. Most notably, the April-December rainfall is the highest for any nine-month sequence in the 247-year series.

2012 as a whole

Notwithstanding the major rainfall deficiencies built up over the January-March period, 2012 was, overall, the second wettest in the NCIC series for the UK; England eclipsed its previous maximum and Wales registered its third highest annual rainfall in a 103-year series. In the EWP series from 1766, only 1872 and 1768 were wetter. Large swathes of England from the south-west to the north-east received over 135% of average rainfall in 2012 (see Figure 26) and record annual rainfall totals were reported for many localities. In Durham, 1,018 mm of rain fell during the year, the wettest in a record from 1880 by an exceptional margin – over 130 mm.[36]

Soil moisture

Soil moisture conditions across most of the country were pivotal in enabling the rapid transformation from drought stress to flood risk through the late spring and early summer of 2012. For Lowland England, the average end-of-month SMDs for April-July established a new minimum in a series which begins in 1961. The singular nature of the transformation in soil moisture conditions is illustrated in Figure 27 which plots the ratio of the average SMDs over the December-March period compared to those for the following four months.

The contrast between 2011 and 2012 in the development and decay of SMDs is also remarkable. Figure 28 illustrates modelled daily SMDs for 2012 calculated using data from the Centre for Ecology & Hydrology's Meteorological Station at Wallingford. In a series beginning in 1972 the degree of disparity between successive years is unprecedented. Considering Lowland England as a whole, soils throughout the summer half-year in 2011 were the driest on record; in

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[u] The 1779 outlier in Figure 25 is due primarily to a remarkably dry and warm late winter; it serves to emphasise the range of departures from average that can be encountered in UK climatic time series.

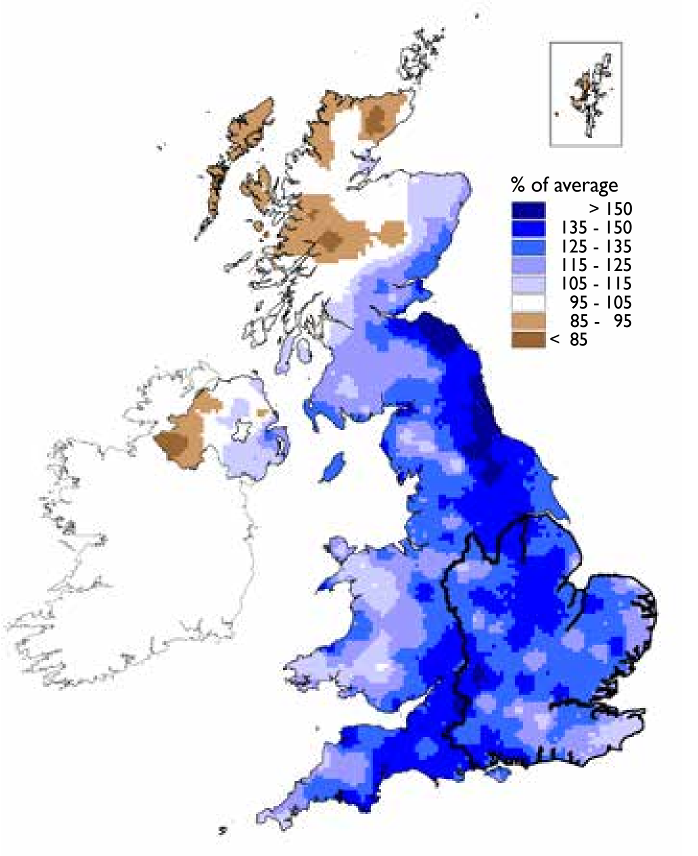

Figure 26 *Rainfall anomaly map (% of 1971-2000 average) for 2012*

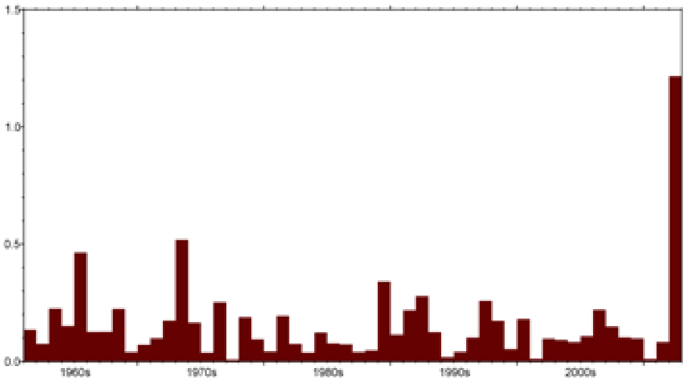

Figure 27 *Ratio between April-July and the preceding December-March SMDs for Lowland England*

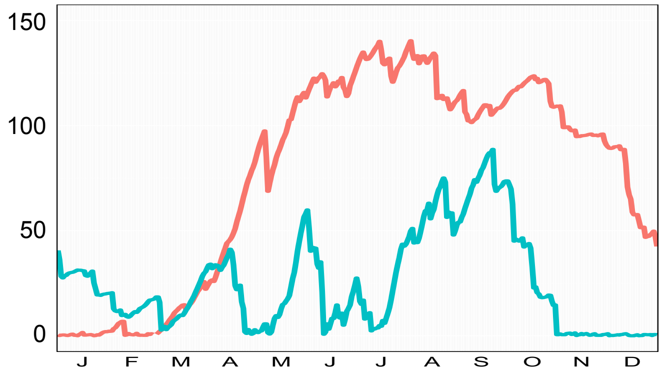

Figure 28 *2011 (red) and 2012 (blue) modelled SMDs (mm) at the Centre for Ecology & Hydrology (Wallingford)*

2012 they were the wettest. The impact on agriculture of the rare soil moisture conditions experienced over the two years was severe but it is salutary to consider that a replication of such soil moisture patterns would have implied widespread malnutrition and local starvation prior to the 20th century.

The very exceptional nature of the soil moisture conditions experienced in 2011-12 is further emphasised by Figure 29 which compares modelled Hydrologically Effective Rainfall (HER)[v] totals for Lowland England over the 1961-2012 period for the winter half-year with those for the following summer half-year. For the former, the HER total in 2012 was the lowest on record, whilst for the latter period a new maximum was established.

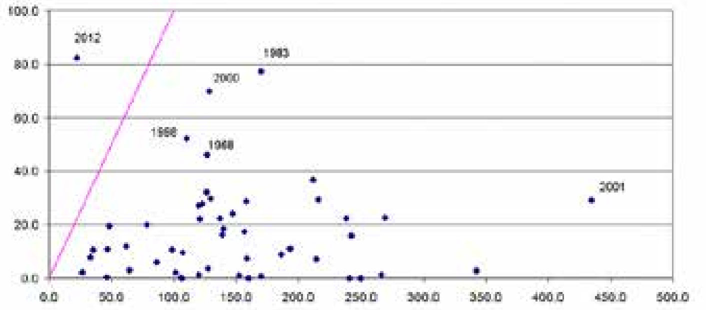

Figure 29 *Hydrologically Effective Rainfall (mm) for Lowland England for the winter half-year (x-axis) and the summer half-year (y-axis), 1961-2012*

Runoff

Years featuring both severe drought conditions and widespread flooding are not uncommon; recent examples include 2003, 1995 and 1990. In 1947, when flood defences were very rudimentary, the most extensive flooding of the 20th century across England & Wales followed one of the coldest (and snowiest) winters on record; snowmelt was the primary cause of the flooding. Subsequently severe drought conditions developed through the spring and summer. The impact on society of these hydrological extremes (particularly the associated crop failures[37,38]) was markedly more severe than the privations suffered during 2012.

Rapid runoff recoveries following droughts are also not particularly rare; instances in the 20th century include 1992[w], 1989, 1976, 1963, 1959, 1929 and 1922. 1963 is something of a special case: the winter of 1962/63 was

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[v] The period between the return to field capacity and the loss of capacity in spring gives the opportunity for rainfall to recharge groundwater and flow to rivers. The sum of rainfall less evaporation during this (mainly winter) period is known as excess rainfall (Hydrologically Effective Rainfall).

[w] In 1992 there was a substantial lag between the sustained rainfall through the late spring and early summer and the associated recovery in runoff and recharge rates.

the third driest in the last 100 years for England & Wales[x] and probably the coldest since 1740[10], with substantial snow accumulations continuing into the second week of March. Frozen pipes exacerbated the water resources stress and water rationing was introduced to moderate demand.[39] Thence in early-March, a rain-bearing warm front triggered a rapid thaw and flows in many rivers climbed from early spring minima to early spring maxima in periods of ten days or less. 1976 provides a more relevant comparison and is of particular significance because of the extreme intensity of drought conditions through the summer and the rapid recovery of river flows during the autumn. In late-August estimated outflows from England & Wales were the lowest on record (for any time of the year[9]) but seven weeks later the mid-October maximum was closely approached (see Figure 30). However, in 2012, the autumn runoff was more than 60% higher than in 1976 and the post-March flooding much more extensive and protracted. Importantly also, none of the recoveries noted above – 2012 excepted – were sustained through the late spring and early summer.

Figure 30 *Outflows ($m^3 s^{-1}$) from England & Wales in 1976 (red) and 2012 (blue)*

Note: envelopes represent daily maxima and minima over the period of record to end of 2011

Extensive and sustained summer flooding has occurred on rare occasions in parts of England & Wales, e.g. in 2007[40], 1968, 1912[35,41] and 1903[41]. In 2007, three consecutive months of very wet weather, with several geographically restricted episodes of extreme rainfall (e.g. across the Midlands and south Yorkshire), resulted in over 55,000 homes and businesses being flooded[42]. Property flooding in 2012 was substantially lower – primarily a reflection of the more even runoff distribution – but outflows from England & Wales over the summer half-year in 2012 were 30% greater than the previous maximum.

At the national scale the runoff patterns experienced in 2012 are without parallel in the period for which realistic assessments of England & Wales outflows can be derived (from 1961). On average, May-July runoff is around 45% of that for the preceding January to March and has never reached 70% prior to 2012 – when it exceeded 150%. Also for the first time, summer half-year outflows for 2012 exceeded those for the previous winter half-year. A longer historical perspective is provided by the flow record for the Thames at Kingston which begins in 1883. Prior to 2012 flows over the May-July period have exceeded those for the preceding January-March in two years only (1903 and 1932). In 2012, May-July flows were more than double those of January-March (see Figure 31). Some parallels may be drawn with 1903 when, following prolonged drought conditions, May-July runoff for the Thames actually exceeded that in 2012 and flooding across southern England was severe, but the terminal phase of the drought was well underway by the late winter of 1902/03.

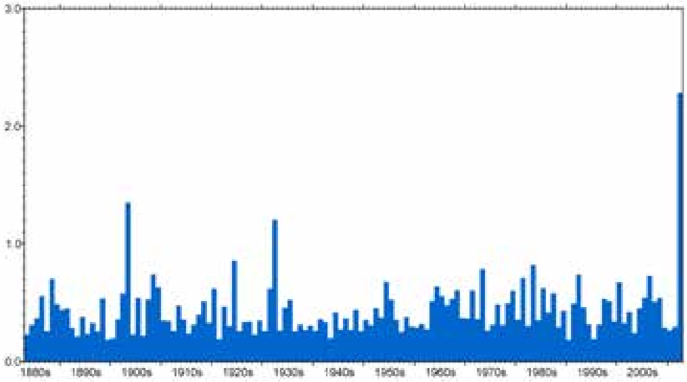

Figure 31 *Ratio between May-July and the preceding January-March naturalised river flows for the Thames at Kingston*

2012 runoff

Despite the depressed flows through the first three months of the year, annual runoff from England & Wales in 2012 was the second highest, after 2000, in the 52-year national series and around 30% of index catchments south of the central lowlands of Scotland exceeded previous annual runoff maxima. A notable index of the singularity of the 2012 runoff patterns is provided by the number of days (48) on which new maximum daily outflows from England & Wales were established; no other year closely approaches this total (see Table 12). In addition, there were 14 days in March and early-April 2012 when previous daily minima were eclipsed.

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[x] Note that precipitation totals may be underestimated where a substantial proportion of the total falls as snow – due to such factors as the freezing of gauges and drifting of the snow.

Table 12 *Numbers of daily maxima and minima, by year, in the outflow series for England & Wales 1961-2012*

Year	Number of daily maxima	Number of daily minima
2012	**48**	**14**
2000	34	0
2007	27	0
2008	24	0
1967	14	0
1981	13	0
1998	12	0
1979	11	0
2002	11	4
2009	11	0

Water resources

Reservoir stocks

Historical comparisons with contemporary reservoir stocks are limited by the length of available records (most nationally-collated series extend over less than 25 years), changing management strategies (groups of reservoirs are increasingly managed as a single unit) and other factors (e.g. maintenance programmes or water quality issues) which can result in reservoir stocks not directly reflecting rainfall or runoff patterns.

Nonetheless it is clear that reversals in the normal seasonal decline in reservoir stocks of the magnitude witnessed in 2012 are exceptionally rare. Estimated overall stocks for England & Wales for late-July were the highest in a series from 1989 by a substantial margin and the previous monthly maxima were eclipsed in each of the following three months, and again in December. Overall stocks at the end of September are, on average, around 65% of those for late-March; for the first time, September stocks in 2012 exceeded those for March. Average stocks over the May-September period clearly exceeded previous maxima for both England & Wales and Lowland England. In the regions where the drought achieved its greatest intensity, the summer recovery in water resources was particularly dramatic. For Lowland England, June reservoir stocks exceeded those for the previous March by a margin not closely approached in a 25-year series (Figure 32).

Groundwater

In a few aquifer outcrop areas, some similarities to the summer half-year recharge patterns experienced in 2012 can be recognised in the groundwater level hydrographs for 2007, 1992 and, more locally, 1968. In the spring of 2007, following two years of generally modest recharge, levels in the Chalk of the Yorkshire Wolds were well below average. The outstanding May-July rainfall then raised summer water tables to levels higher than those reported in 2012. However, across the country as a whole, groundwater resources were already healthy in the spring of 2007 and the spatial extent of the late spring and summer groundwater level recoveries was much more restricted than in 2012.

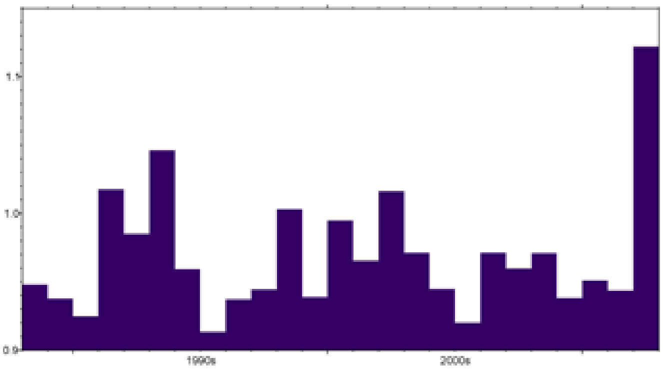

Figure 32 *Ratio between June and the preceding March reservoir stocks for Lowland England*

In many of the faster-responding aquifers, the summer recoveries in 2012 were clearly unprecedented. By July, new monthly maximum levels were recorded in a significant proportion of index wells and boreholes across England & Wales (see Figure 24a). These included Ampney Crucis in the Jurassic Limestone of the Cotswolds (with a 53-year record) and West Woodyates in the western Chalk (68 years). Considering the Chalk outcrop as a whole, the magnitude of the 2012 recovery in groundwater resources was truly exceptional (Figure 33). Based on data from a network of widely distributed wells and boreholes across England, the increase in groundwater storage through 2012 was the largest for any 12-month sequence in a series from 1942, and considerably exceeded the generally steeper but less sustained recovery following the 1976 drought. As notably, by late-December overall storage in the Chalk closely approached the record maxima registered in 1960 and 2000.

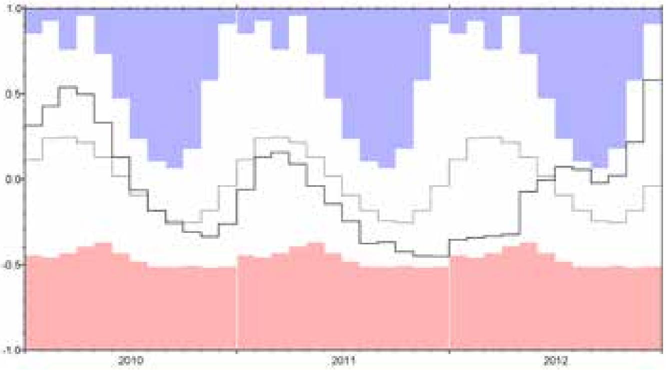

Figure 33 *An index of monthly mean groundwater levels for the Chalk*

A particularly lengthy historical perspective is provided by the groundwater level record for the Chilgrove House well in the Chalk of the South Downs.[43] Beginning in 1836, it has one of the longest continuous records in the world and typifies those monitoring sites which respond quickly to recharge. Having approached natural base levels in early-April 2012, levels rose around 15 metres through the first half of May, more than twice the previous maximum May increase in the 178-year series. Subsequently average levels in both June and July exceeded previous monthly maxima[y]. Confirmation of the extraordinary summer recoveries in southern England is provided by the nearby Compton House well: the average summer groundwater level in 2012 was more than seven metres higher than the previous summer maximum in a 119-year series (see Figure 34).

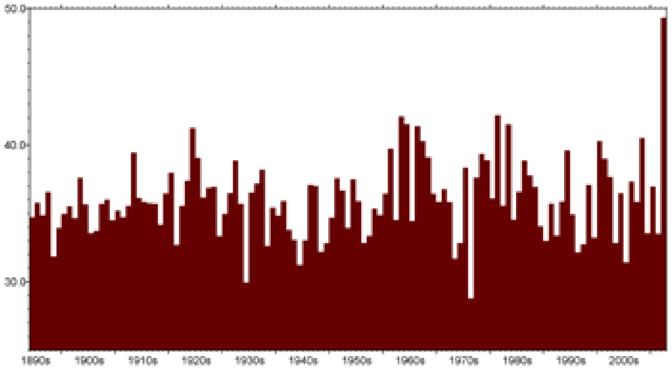

Figure 34 *Average June-August groundwater levels (m aOD), Compton House (West Sussex)*

Storage in soils and groundwater

Spatial variations in the recoveries of runoff and aquifer recharge through the summer half-year in 2012 were considerable and cannot be fully captured by the UK network of index wells and boreholes. Figure 35 provides a much finer spatial resolution using modelled estimates of monthly storage[z] changes across the UK[44]. The storage anomaly maps illustrate the extent and magnitude of the storage deficiencies in the early spring of 2012, and the transformation three months later. The residual deficiencies in July generally reflect the continuation of drought conditions in north-west Scotland and the very uneven distribution of rainfall across Lowland England. For England as a whole the increase in modelled storage over the April-July period in 2012 was greater than for any four-month sequence in a series from 1971, exceeding that for September-December 1976 by a significant margin.

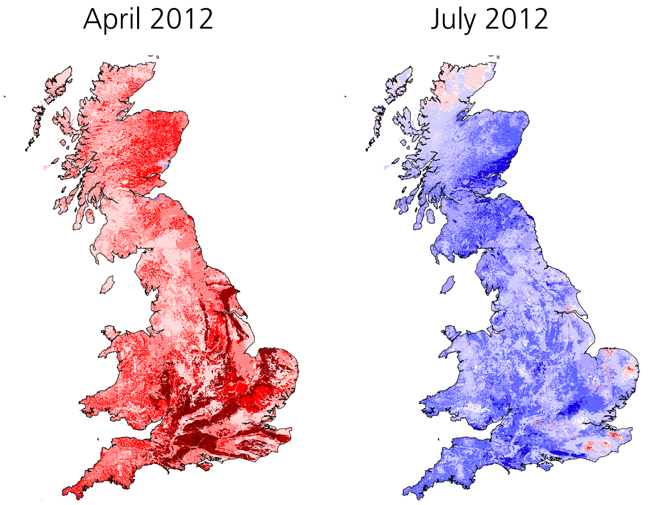

Figure 35 *Storage anomaly maps based on modelled estimates of monthly storage changes*

Note: the intensity of red shading indicates the degree of storage deficiency; the blue shading indexes storage surplus

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[y] For much of the historical record monthly averages are based on single level readings only.

[z] Here taken to mean water stored in the soil and groundwater (including water in the unsaturated zone).

THE RECENT PAST IN THE CONTEXT OF LONG-TERM HYDROMETEOROLOGICAL TRENDS

Overview

Rainfall, runoff and aquifer recharge patterns across the UK were particularly volatile over the ten years ending in 2012; the period included three notable droughts (2003, 2004-06, 2010-12) and a cluster of damaging flood episodes (e.g. Boscastle, 2004; north-west England 2005; central and northern England, 2007; north-east England and Northern Ireland, 2008; Cumbria, 2009). The hydrometeorological conditions experienced through the early years of the 21st century attracted considerable public attention and remained high on the political agenda. With temperature increases over the last 50 years being exceptional it is understandable that causative linkages are made between the weather patterns of the recent past and global warming. But variability, expressed over a wide range of timeframes, is a defining feature of the UK climate and lengthy instrumental records are punctuated by flood- and drought-rich periods, some clustering within the same decade.

Identifying compelling long-term trends in drought and flood magnitude and frequency in the UK remains a considerable scientific challenge. In this section the observational evidence of changes in temperature, rainfall and runoff and, less extensively, recharge patterns is reviewed together with a consideration of possible causative factors which may be influencing the temporal changes.

Temperature trends

Annual average central England temperatures from 1659[10] are shown on Figure 36. The series exhibits considerable variability: the 1740s and 1840s were particularly warm but over the last 120 years temperatures have increased by around 1.3°C with a particularly steep rise over the latter half of the 20th century. This period, crucially, saw mean temperatures move beyond the range of variability captured in the first 300 years of the record. Importantly in the context of the hydological implications, the great majority of available river flow and groundwater level data has been collected during the recent period of enhanced warming.

High temperatures have certainly contributed to drought stress in the UK but important gaps remain in our understanding of how temperature changes have, and will, impact on rainfall and runoff patterns. In addition there are substantial uncertainties associated with modelled projections of future temperatures, in part reflecting the difficulties in assessing future increases in greenhouse gases. Nonetheless, the rise in temperatures in the UK (as elsewhere) has been exceptional over the latter half of the 20th century[45] and is consistent with the expectation of a significant anthropogenic warming signal in this temperature increase.[46]

Rainfall trends

Rainfall patterns across much of the country during the 2010-12 period approached the extreme range captured in historical datasets but most long rainfall series are characterised by substantial variability about a relatively stable long-term mean. Few compelling trends are identifiable in the annual EWP series (see Figure 37) but it is evident that variability is considerable, with some very wet episodes (e.g. the 1870s) and very dry episodes (e.g. the early 1960s to mid-1970s) but with little indication of an overall trend.[45]

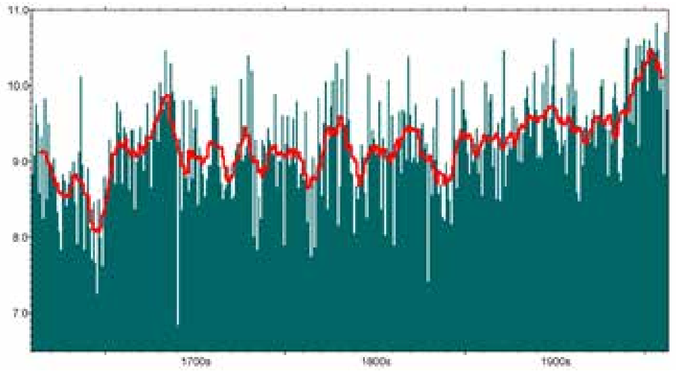

Figure 36 *Average annual Central England Temperature (°C), with 10-year running mean*

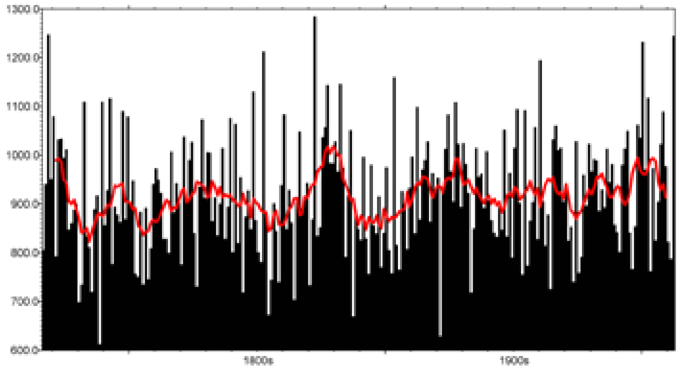

Figure 37 *Annual rainfall (mm), England & Wales Precipitation (EWP) series, with 10-year running mean*

Seasonal rainfall totals are also highly variable. Winter (December-February) rainfall totals exhibit a slight overall increase, particularly for the duration of the 20th century compared to the 19th century but a contributory factor may be the greater proportion of snowfall in the early part of the record (snowfall tends to be systematically underestimated due to measurement difficulties[aa]). The sparseness of the raingauge network (particularly in the wettest areas) prior to the 1830s also implies a greater measure of uncertainty in the early areal rainfall assessments. Summer rainfall has exhibited a slight overall decrease reflecting, in particular, the relative dryness of the summers in the 1970s, 1980s and 1990s. However, the last decade has seen a preponderance of relatively dry winters in England & Wales (whilst Scotland has registered several notably wet winters) and a cluster of years with wetter than average summers – 2007 to 2012 is the longest sequence of summers with rainfall exceeding the 1971-2000 average in the NCIC series.

In the context of drought and flood vulnerability the partitioning of the rainfall between the winter and summer half-years is important; wetter winters are associated with both increased flood risk and, in many areas, a moderation in drought vulnerability through the following summer – a consequence of very healthy reservoir stocks and groundwater resources early in the year. Figure 38 shows 10-year running means for the November-April and May-October[ab] rainfall totals for England & Wales. The 30 years from the mid-1970s featured a considerable increase in 'winter' rainfall but the full record shows substantial variations in the half-yearly partitioning; May-October rainfall totals normally exceeded those for the 'winter' prior to the 20th century. Wet sequences of months during the summer half-year were more frequent prior to the 20th century, and cluster notably in the late 18th century.

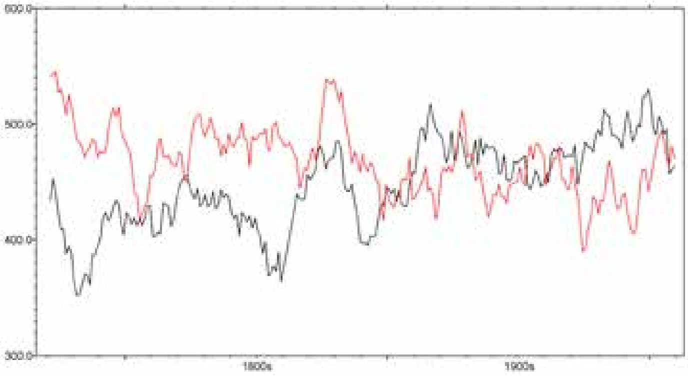

Figure 38 *10-year running means of November-April rainfall (mm; black) and May-October rainfall (mm; red), England & Wales Precipitation (EWP) series*

The limited evidence for sustained long-term trends in rainfall serves to emphasise that the link between temperature and rainfall trends in the UK is relatively weak. The modest increase in rainfall over the latter half of the 20th century is encouraging from a water resources perspective, particularly the tendency for 'winter' rainfall to increase. However any projection of this tendency needs to be undertaken with considerable caution given both the variability captured in the EWP series and the known association between winter rainfall, especially in northern and western areas, and pressure gradients across the North Atlantic.[48] These are indexed by the North Atlantic Oscillation (NAO) which has recently switched from a predominantly positive to a negative phase (see Figure 39); this may imply an increasing frequency of drier winter half-years in northern and western Britain.

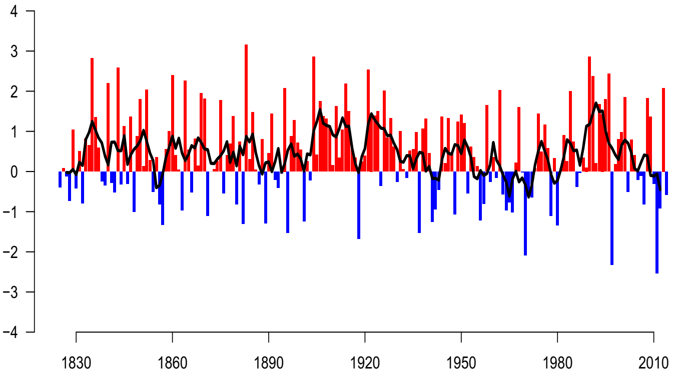

Figure 39 *North Atlantic Oscillation (NAO) index*

Data source: Climate Research Unit

Trends in heavy rainfall

Rainfall intensity is a major factor in relation to flood risk and a number of studies have identified a tendency for a higher proportion of rainfall to fall in more intense events.[49,50] There is considerable regional variability in these changes with evidence of decreases in intensity in some regions[51]; a feature of most studies is that the greatest increases are in northern and western localities, and especially pronounced at upland sites.[52] There are also seasonal contrasts, with the greatest increases are in winter.[53] Recent work also points to increasing rainfall intensity in spring and autumn, but these tendencies are less compelling[49]. Most studies have found no significant changes in summer rainfall intensity, although decreases in short-duration (1-day) summer rainfall intensity have been noted[49]; these contrast with increases in longer duration (e.g. 10-day) events. Most published studies end in 2009 at the latest, but more recent work by the Met Office National Climate Information Centre (in preparation) includes data for 2012 and has found a slight increase in the number of 'extreme' rainfall days across the UK (defined by the 99th percentile of wet days). This is due to a slight increase during the winter season (December-February), whereas there are no notable trends in extreme rainfall for spring, summer or autumn.

[aa] Rainfall, as measured in standard rain gauges is systematically underestimated relative to ground level gauges[47] but the underestimation of snowfall, though difficult to quantify, is substantially greater.

[ab] Chosen to illustrate changes in the periods which are most important in relation to runoff and recharge.

Evaporation and catchment losses

River flows and aquifer recharge patterns reflect the balance between rainfall and evaporation losses – which, in turn, are influenced by a range of factors including temperature, humidity, wind speed and land use. Whilst modelled assessments of potential evaporation have increased over the last 50 years, actual evaporation losses – as indexed by lysimeter studies[54] and both catchment[55] and national water balances[56] – exhibit only a limited trend.

Runoff trends

River flow records in the UK do not provide a comparable historical perspective to that available for rainfall. However the relatively dense hydrometric networks in place by the 1960s, complemented by several more extended time series, provide a strong observational foundation upon which to examine runoff variability over the last 100 years or more. Importantly however, the variability in the river flow time series is such that any apparent tendency for runoff to increase or decrease can be very sensitive to the period of record under review.

The ready availability of hydrometric data has facilitated a wealth of research directed at understanding changes in river flow patterns in the UK over the last 50 years. A comprehensive recent assessment[57] found evidence of significant trends in some river flow indicators (e.g. in winter runoff from the 1960s to present) but very little compelling evidence for long-term increases in fluvial flood magnitude or of drought severity, and no strong evidence for any anthropogenic warming signal in river flow time series thus far. Whilst, to date, no published trend studies have featured the 2012 events, it is unlikely their inclusion would change the conclusion that there is, as yet, no compelling evidence for long-term trends.

Figure 40 shows annual mean, Q_{98} and Q_2 flows (commonly used indices of low and high flows) for England & Wales; the plots incorporate flows for 2012. The time series, supported by similar data from more extended datasets for individual catchments[58] exhibit considerable multidecadal variability but no significant overall trend. Over the post-1960 period runoff has tended to increase significantly in Scotland (largely due to enhanced winter runoff), modestly for Wales, and shown virtually no change for England or Lowland England. The lack of any decrease in runoff is encouraging from a water resources perspective. However, the early 1960s and mid-1970s were characterised by a relatively high frequency of dry winters and any subsequent increase in runoff may also be a reflection of natural climate variability, particularly given the changes in the NAO over the last 50 years.

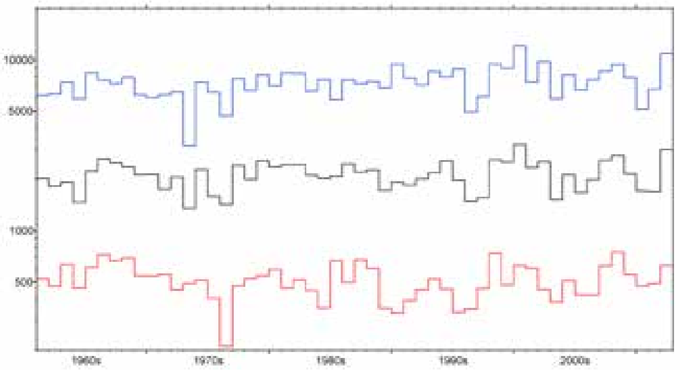

Figure 40 *Annual Q_2 (blue), Q_{50} (black) and Q_{98} (red) outflows ($m^3 s^{-1}$) from England & Wales*

Low flows have exhibited notable year-on-year contrasts in the 21st century thus far but over the 1961-2012 period there is no clear trend in low flows from England & Wales.[57,58] For Lowland England spring runoff has tended to decrease since the 1960s but the decreases are not evident in lengthier historical series.[59] Whilst changes in low flow regimes due to artificial influences (e.g. increasing abstraction rates or low flow augmentation schemes) can readily be identified, analyses undertaken for rivers where the impact of abstractions and discharges on low flows is relatively minor are consistent with the national picture.

Studies using long hydrometric records, alongside records extended using historical reconstructions of flood magnitude based on documentary and epigraphic sources (e.g. flood marks)[60], or relationships with atmospheric drivers[61,62], testify to notable clustering of flood-rich and flood-poor periods and considerable inter-decadal variability in flood frequency. There has been an increase in the frequency of high flows since the mid-1960s / early-1970s – a period which had an atypically low frequency of high flows. Importantly however, any increasing tendency in high flows should not be taken to necessarily imply an increasing flood risk. Whilst recent increases in the frequency of high flows have been identified in many UK catchments[57], a majority of studies have not shown any long-term trend in the magnitude of UK floods. For the Thames, there has been a significant long-term increase in the frequency of flows exceeding the Q_5 threshold but no trend is evident in the series of water year maxima[63] (see Figure 41). Though difficult to quantify, one factor of relevance is the decline of snow cover as temperatures increase across the UK – and a corresponding decline in snowmelt as a causative, or contributory, factor in major flood events.

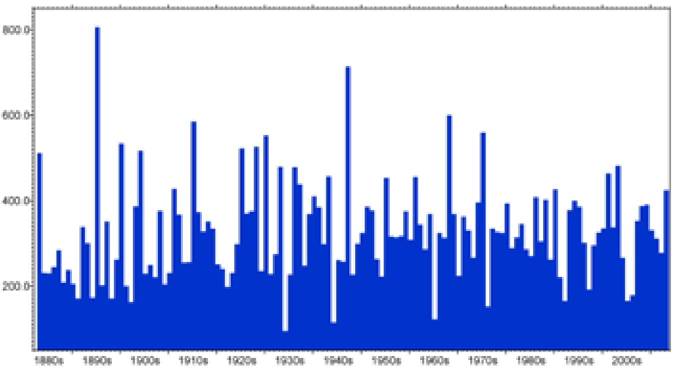

Figure 41 *Water year maximum naturalised daily flow ($m^3 s^{-1}$) for the Thames at Kingston*

Groundwater level trends

Compelling trends in groundwater levels are readily identifiable in those parts of the country where groundwater abstraction regimes have changed markedly over time. Heavy groundwater abstraction from the Chalk below London resulted in a 70 metre decline in groundwater levels at Trafalgar Square over the period from the 1830s to the 1950s[64]. Levels recovered subsequently as water supplies were primarily drawn from the Thames. More moderate long-term declines and recoveries in groundwater levels have been noted for other conurbations and in old mining areas (as pumping to remove water from the mines was discontinued).

Relatively little is known about how groundwater has responded to climate change – groundwater systems are naturally very variable and may be expected to respond to increasing temperatures in a complex manner.[65] Nonetheless where abstraction rates have little impact on natural groundwater levels, evidence for long-term trends is much weaker. Figure 42 illustrates annual mean groundwater levels for a number of index wells and boreholes with records in excess of 50 years. The poorer quality of the early groundwater level data and the variations in sampling frequency over time imply that any apparent trends need to be treated with caution. However, the series share a number of characteristics – for example notably low levels in the 1930s and 1970s and exceptionally high mean levels for 2012. Monthly groundwater level time series suggest an enhanced degree of seasonal variability over the last 25 years but there is little evidence of any long-term trend. A confirmatory picture emerges when the time series of estimated overall storage in the Chalk is examined (Figure 43).

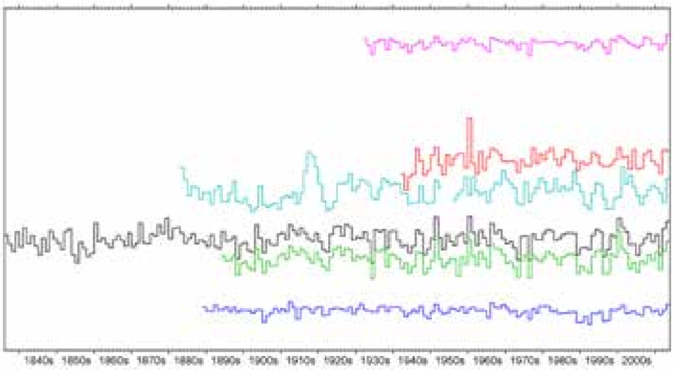

Figure 42 *Annual mean groundwater levels for Rockley (pink), West Woodyates (red), Therfield Rectory (light blue), Chilgrove House (black), Compton House (green) and Dalton Holme (blue)*

The recent past has witnessed a relatively high frequency of groundwater flooding episodes (e.g. in 1995, 2001 and 2012) but given the relative rarity of such episodes, and the limited availability of groundwater level data prior to the 1960s, it is currently unclear whether this is a reflection of climatic variability or indicative of an increasing frequency in exceptionally high groundwater levels.

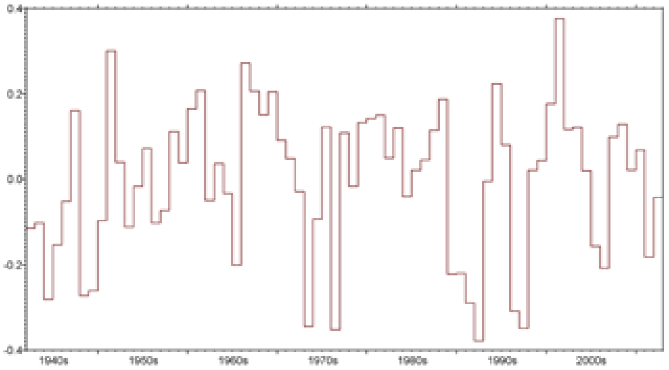

Figure 43 *An index of annual mean groundwater levels for the Chalk*

Discussion

The very sustained drought conditions experienced in 2010-12 and the persistent flooding that followed could simply reflect natural variability of the UK climate. A multitude of influences from both the neighbouring North Atlantic and also from tropical weather patterns, and climate events such as El-Nino Southern Oscillation, have been shown to affect northern Europe. The degree to which such influences will intensify or moderate in a warming world remains uncertain. Future temperature changes may be expected to reflect not only increasing surface temperatures but changes in vertical temperature gradients (as the upper atmosphere warms at a greater rate) and horizontal gradients in temperature between the sub-tropics and the Arctic as the loss of sea ice and snow cover contribute to a faster rate of warming in high latitudes. For the UK, the impact on the favoured tracks and the strength of the Jet Stream may be especially influential. Correspondingly, there are considerable uncertainties relating to the hydrological impact of rising temperatures; this is a focus of much current research effort.

Recent research suggests that the persistent, anomalous patterns in the Jet Stream associated with both the drought conditions in 2010-12, and the subsequent summer flooding, could be related to 'Arctic amplification' associated with sea ice loss.[66] This research is ongoing, and the association has been challenged[67] but in general it suggests that recent anomalous weather patterns in the UK, alongside wider phenomena in northern Eurasia (e.g. the Russian heatwave of 2010) and North American droughts of 2011-12, may be associated with changes in the position and persistence of the Jet Stream, caused by changing temperature gradients.

A general shift to a pattern of wet summers in northern Europe and hot dry summers in southern Europe since the 1990s[68,69] has coincided with a marked warming of the North Atlantic related to the Atlantic Multidecadal Oscillation (AMO); a similar state was last seen in the 1950s, a period which also contained a number of relatively wet summers for the UK (e.g. 1956 to 1958). Warm sea surface temperatures in the North Atlantic in spring have a tendency to drive lower pressure and heavy rainfall across the UK and Europe.[69] Recent work suggests the clustering of relatively wet summer half-years from 2007 to 2012 are associated with changes in atmospheric circulation linked with the recent warm anomalies in the AMO[70].

However, disentangling the effect of the many, often competing influences, is extremely complicated. In addition, the association between rising temperatures and drought and flood risk across the UK is complex. In a warming world, the risk of tidal flooding is increasing (as sea levels rise) but there is considerable uncertainty about future changes in the frequency of extreme rainfall events. A number of recent climate modelling studies have predicted that such events are likely to become more frequent in the UK – particularly during the winter – but the proportion of summer rainfall falling in intense storms may also increase the risk of local drainage networks being overwhelmed; urban areas are particularly vulnerable to flash flooding.

Changes in vulnerability to drought and flooding across the UK are significantly affected by factors other than climatic change or variability. Demographic change and projected increases in water demand, together with the dearth of major reservoir construction over the 30 years since the early 1980s, is narrowing the margin between resources and demand. Continuing floodplain development and urban growth has contributed to the rapidly rising economic costs of both pluvial and fluvial flood events. At the same time, and particularly over the last 50 years, improvements in river management (e.g. channel re-profiling and re-alignment, more efficient weir design) have increased the capacity of many river channels. As a consequence flows in the lower Thames, for example, which would have caused substantial floodplain inundations in the 1940s can now be readily contained within bank[63]. Such developments, together with other innovative flood alleviation measures (e.g. the deployment of de-mountable barriers) and improved forecasting capabilities, have significantly moderated the impact of major flood episodes.

CONCLUSION

The continuing vulnerability of the UK to extreme weather patterns was underlined over the 2010-12 period. Notable drought conditions, over a wide range of durations, affected most parts of the UK during the two-year period to March 2012. The drought culminated in the early spring, at a critical time in relation to water resources and agriculture in particular. The impact of the rainfall deficiencies on the environment and on wildlife, which now assume a considerably greater importance than in earlier drought episodes, was also severe. Even with normal rainfall through the summer half-year of 2012, significant economic and ecological stress would have occurred; this would have been compounded in the event of a third successive dry winter. However, a dramatic and unforeseen change in synoptic patterns then heralded the wettest nine-month sequence in England & Wales in almost 250 years. The resulting hydrological transformation through the late spring and summer has no close modern parallel. Flooding affected almost all regions and was remarkably sustained across much of England through the remainder of the year.

The efficacy of amelioration measures to moderate the impacts of the extreme hydrological conditions was well demonstrated in 2010-12. Nonetheless, there is a continuing need to increase the UK's resilience to the threat of drought and floods. Improved modelling and forecasting capabilities, predicated on a fuller understanding of the causation and impacts of drought and flood episodes, provide a necessary foundation for more effective and economically sustainable water management strategies.

Some reassurance may be gained from the fact that the conditions that conspired to make the 2010-12 period so exceptional were close to the extreme range of historical variability and that there is, as yet, limited evidence for long-term trends in rainfall, river flows and groundwater levels. It is nonetheless imperative that monitoring programmes are maintained and strengthened to identify and quantify changes in rainfall, runoff and aquifer recharge patterns in a warming world.

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The credibility of any examination of major drought and flood episodes is heavily dependent on the availability and quality of a wide range 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.

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Photo Credits

Plate I	Terry Marsh
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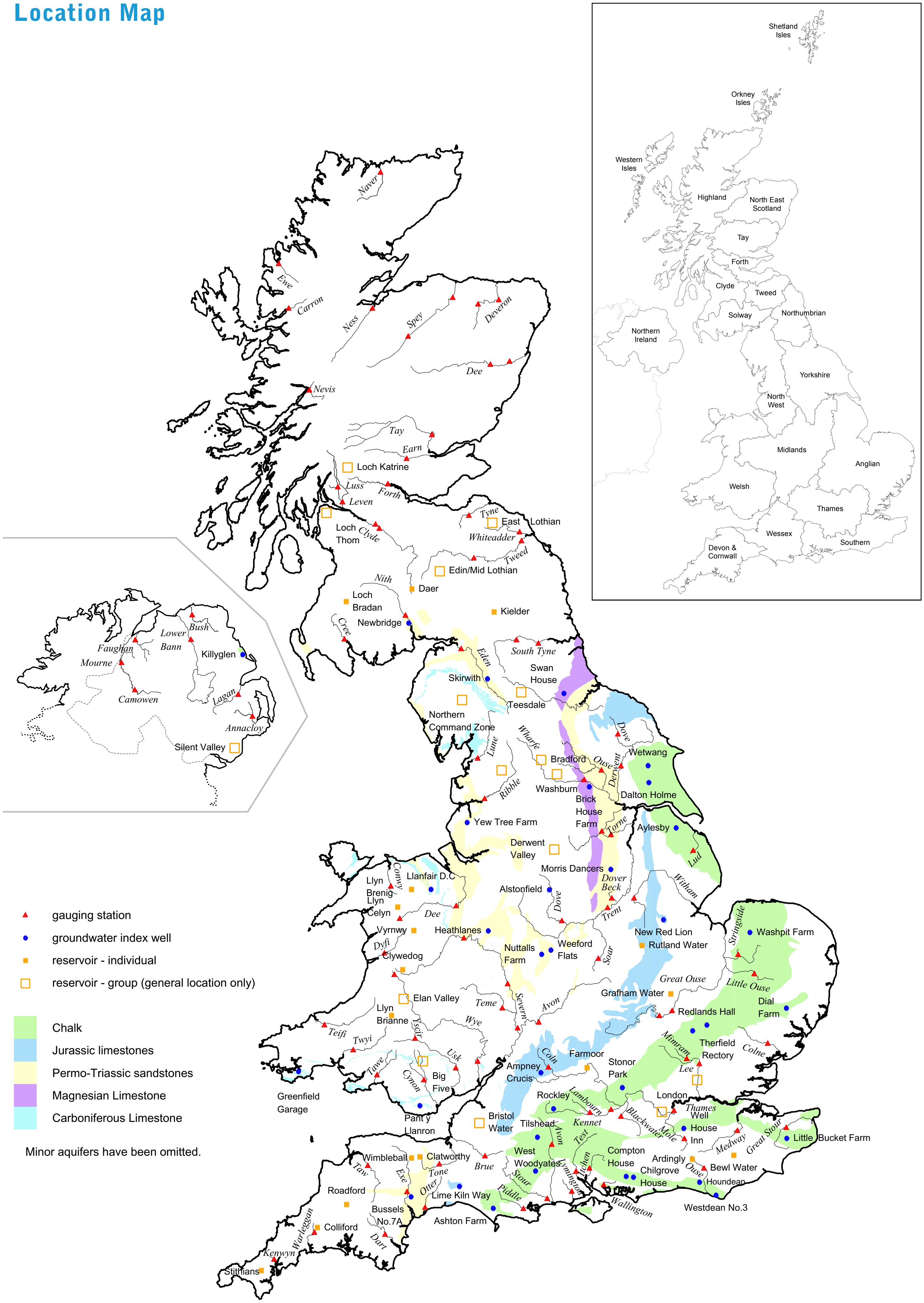
Location Map



Minor aquifers have been omitted.

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