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Climate-driven changes in UK river flows: A review of the evidence

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Abstract
There is a burgeoning international literature on hydro-climatic trend detection, motivated by the need to detect and interpret any emerging changes in river flows associated with anthropogenic climate change. The UK has a particularly strong evidence base in this area thanks to a well-developed monitoring programme and a wealth of studies published over the last 20 years. This paper reviews this research, with a view to assessing the evidence for climate change influences on UK river flow, including floods and droughts. This assessment is of international relevance given the scale of the research effort in the UK, a densely monitored and data-rich environment, but one with significant human disturbances to river flow regimes, as in many parts of the world. The review finds that changes can be detected in river flow regimes, some of which agree with future change projections, while others are in apparent contradiction. Observed changes generally cannot be attributed to climate change, largely due to the fact that river flow records are limited in length and the identification of short-term trends is confounded by natural variability. A UK 'Benchmark' network of near-natural catchments is an internationally significant example of an initiative to enable climate variability to be discerned from direct human disturbances (e.g. abstractions, dam construction). Generally, however, the problem of attribution has been tackled rather indirectly in the UK, as elsewhere, and more efforts are required to attribute change in a more rigorous manner.

Keywords
climate change, drought, flood, river flow, trend, UK

I Introduction

Anthropogenic climate change is expected to intensify the hydrological cycle (Huntington, 2006), leading to modified river flow regimes in many parts of the world. Changes in the water or energy balance could alter the magnitude, timing and seasonal distribution of river flows, while more intense rainfall could lead to increased flood severity. However, there are considerable uncertainties in modelled projections for future climate change (e.g. Watts et al., In press; Wilby et al., 2008) and there are gaps in our understanding of how climate change influences river systems. There is a complex, non-linear chain from increasing temperatures, through related changes in weather patterns, to flow response; with river catchments playing a significant, and often poorly understood, role in modifying climate signals. There is vital need, therefore, for observation-based studies of long-term changes in river flow, in order to discern any emerging trends

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and to provide 'ground truth' for scenario-based model outputs.

River flow regimes are a key indicator of potential impacts of anthropogenic climate change. River flows represent the integrated response of all hydrometeorological processes acting upon a catchment, and it is through altered river flow regimes that climate change could have some of the most profound impacts on society, due to increases in flood risk, decreases in water availability and degradation of water quality and ecosystem services. Consequently, there is a burgeoning literature on the subject of change in river flow regimes. A recent review identified 128 studies of long-term trends in river flow regimes, globally (Burn et al., 2012). In the UK, river flow change has been a focus of a substantial research effort: there are few parallels, internationally, to the quantity and breadth of studies (relative to the size of the land area under consideration) carried out on hydro-climatic change in the UK.

The aim of this paper is to provide a state-of-the-art assessment of the evidence for long-term river flow changes in the UK, focusing on climate-driven changes in flow, as opposed to changes caused by direct human disturbances such as water management practices (e.g. abstraction, effluent returns, impoundments), land use or land management. The paper reviews evidence for changes through the 20th century and up to 2012, although brief consideration is also given to changes earlier than 1900. The paper begins with some background on the data and methods that are commonly used in assessments of hydrological change. The review of the evidence then considers changes in: annual and seasonal runoff; high flows and indicators of flooding; low flows and indicators of drought. Attribution of observed trends is then discussed – posing the question of whether observed changes are consistent with currently favoured projections under anthropogenic warming.

II Data and methods for change detection

The UK has an exceptionally dense river flow gauging station network by international standards. The principal archive of hydrometric data for the UK is the National River Flow Archive (NRFA) (Dixon et al., 2013), which holds data for around 1400 gauging stations. From the perspective of hydrological change detection, however, this rich information resource is compromised by a number of factors. The monitoring network expanded rapidly in the 1960s and 1970s, and only a handful of records began in the 1930s or earlier. The quality and homogeneity of longer flow records is typically compromised by changes in gauging practices. Efforts have been made to extend the temporal coverage of river flow records by reconstructing river flows using rainfall-runoff models, as long rainfall records are more plentiful. For example, monthly river records extending back to 1865 have been reconstructed for 15 catchments in England and Wales by Jones and Lister (1998) and Jones et al. (2006).

In addition to record length constraints, poor data quality can hinder hydrological change detection. While hydrometric monitoring capabilities in the UK are generally very high by international standards, inaccuracies are an inevitable feature of many gauged time series. Furthermore, poor quality and missing data tend to cluster disproportionately in the extreme flow ranges, hampering the assessment of long-term changes in high and low flows in particular (Dixon et al., 2013). An additional constraint, one shared by many other developed countries, is that the UK is densely populated and human disturbances on runoff patterns are pervasive. Artificial influences (for example, changing abstraction patterns) can lead to spurious trends which bear little relation to climate variability. An attempt to overcome these obstacles has been made with the definition of a 'Benchmark' network, a subset of around 130 stations on the

NRFA designated as a reference hydrometric network (RHN – for an international review of networks of this type, see Burn et al., 2012, and Whitfield et al., 2012) to allow climate-driven trends to be distinguished from direct anthropogenic impacts. Benchmark catchments have near-natural flow regimes, and are gauged by stations which produce good-quality data (see Bradford and Marsh, 2003, for a description of the network).

Analyses of long-term change in hydro-climatic time series typically use some form of statistical methodology, such as the Mann-Kendall test, to test for non-stationarity (the reader is referred to general reviews of hydro-climatic change detection methods for descriptions of these methods, e.g. Kundzewicz and Robson, 2004). It is important to note that such methods have inherent limitations, and the literature abounds with discussion on the appropriateness (or otherwise) of hydro-climatic trend tests (e.g. Burn et al., 2012; Cohn and Lins, 2005; Hirsch, 2011; Merz et al., 2012). The detailed statistical issues are not addressed here but it is important to note several general points, which should be considered in assessing the evidence for climate-driven changes in UK river flows. Kundzewicz and Robson (2004) recommend 50 years to detect a climate-driven change, but most UK records fall short of this. It could be argued that even 50 years is too short; numerous authors have cautioned that a trend in a given period may represent part of a longer-term pattern of inter- or multi-decadal variability (e.g. Chen and Grasby, 2009; Hannaford et al., 2013). Moreover, Wilby (2006) notes that hydro-climatic series exhibit low signal-to-noise ratios, and therefore trends may be obscured by random variation (Radziejewski and Kundzewicz, 2004). This may mean that changes are not detectable, in a formal statistical sense, but may still be exerting an effect which is relevant for water management.

The combination of short records, methodological constraints and data quality issues is a real obstacle to the attribution of change. Data quality limitations can be overcome to a certain extent, through judicious selection of catchments (i.e. using an RHN such as the Benchmark network). Nevertheless, the methodological constraints, particularly the confounding influence of multi-decadal variability, must always be at the forefront of the interpretation of any analysis of long-term change. Attribution of detected trends is therefore a particular challenge, as discussed in relation to the UK evidence base in section VI.

III Annual and seasonal runoff

Annual and seasonal runoff are perhaps the most simple indicators of overall water availability, and provide a good starting point for assessing hydrological change. Marsh and Dixon (2012) recently conducted an analysis of trends in national outflow series, computed by aggregating the flows of major gauged rivers and using a hydrological model to account for ungauged areas, thus providing a foundation for assessments of changes in runoff at very broad scales for the UK (Table 1). Outflows increased over the 50-year period 1961–2011 for Scotland, Wales and Great Britain as a whole. However, only the trend for Scotland is statistically significant. The general trend from the outflows can be compared with a previous national-scale assessment of annual runoff trends across the Benchmark network (Hannaford and Marsh, 2006) for two study periods (1963–2002 and 1973–2002). These results were consistent with the national outflow series: there was evidence for increasing annual runoff trends in catchments in the upland, strongly maritime-influenced areas of northern and western Britain, with particularly strong increases in Scotland, from both study periods. In both studies, the increased runoff from upland areas contrasts markedly with southern and eastern England. The total outflows series for the English lowlands showed no annual runoff trend, and there were very few significant trends from

Table 1. Changes in various flow indicators for the total outflows series, 1961–2010 (based on the data discussed in Marsh and Dixon, 2012). Values show the change over the course of the record expressed as a percentage change in the long-term mean. Bold indicates significance at the 95% level (using Mann-Kendall trend test).

	Scotland	Wales	England	English lowlands
Annual runoff	**22.2**	14.7	1.7	0.9
Winter	**44.7**	21.6	23.5	14.3
Spring	6.7	–6.5	–15.1	–16.3
Summer	2.4	8.2	–11.2	–6.8
Autumn	16.7	35.3	7.9	17.4
High flows (Q5)	**22.4**	**26.5**	13.8	6.3
Low flows (Q95)	3.9	4.8	–12.0	–9.1

Benchmark catchments anywhere in central, southern or eastern England.

While annual runoff gives an indication of overall water availability, it masks much within-year variability; climatic changes may modify the seasonality of flow regimes and the individual seasonal changes could be important for different aspects of water management. Seasonal runoff trends were examined for the national outflow series (Table 1): strong increases were observed for winter (although this was only significant for Scotland), weaker increases in autumn and generally weak evidence for change in summer, although decreases were observed for England and the English lowlands. Hannaford and Buys (2012) examined trends in the Benchmark network for a 1969–2008 study period – a summary of trends in seasonal runoff is shown in Figure 1. Once again, the strongest increases were seen for the winter half-year: winter runoff increased in upland, northern catchments, while autumn runoff increased across much of the UK. Spring runoff decreased across lowland England, although trends were weak in many catchments. Summer presented an extremely mixed picture, with no regionally coherent patterns in the English lowlands.

The above studies are limited to the post-1960 period, when a dense network of gauges is available for characterizing spatial patterns in trend responses. The seasonal trend analysis for Benchmark catchments (Hannaford and Buys, 2012) was complemented by eight long NRFA records extending back to the 1930s. These analyses generally confirm the more recent increasing trends, for winter and autumn, whereas the recent spring decreases are not seen in longer records – there is evidence of a shift, from increasing runoff trends from the 1930s to the 1960s to decreasing runoff since. Long summer flow records (Hannaford and Buys, 2012) show very mixed patterns and generally rather weak trends. An even longer perspective is provided by reconstructed records (Jones et al., 2006) extending back to 1865. Wilby (2006) examined trends in moving windows, for every possible start year of these records, for annual, winter and summer mean flows, as shown in Figure 2. While the number of significant trends is modest, there is a general tendency towards increasing annual runoff and winter runoff across all start years. Summer trends are generally much more mixed, and there is limited evidence for any pronounced changes although significant decreases are apparent in some catchments.

IV High flows and indicators of flooding

In the recent past, flooding has been at the forefront of public attention in the UK, and there is a

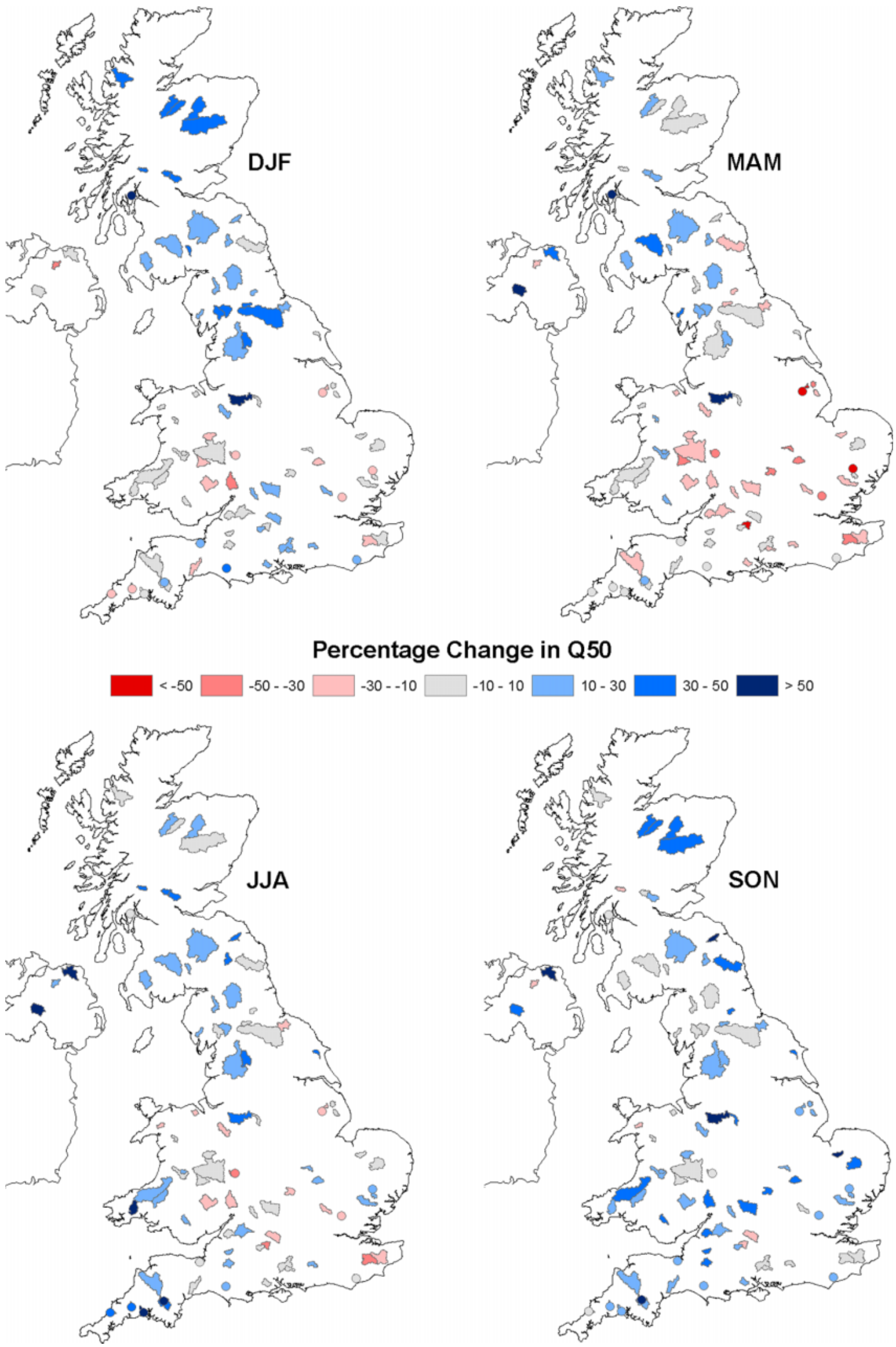

Figure 1. Seasonal runoff trends (seasonal median flow, Q50) in the Benchmark network, 1969–2008 (Hannaford and Buys, 2012). Trend magnitudes computed using the Thiel-Sen estimator of trend slope and expressed as a percentage of the long-term mean in the Q50.

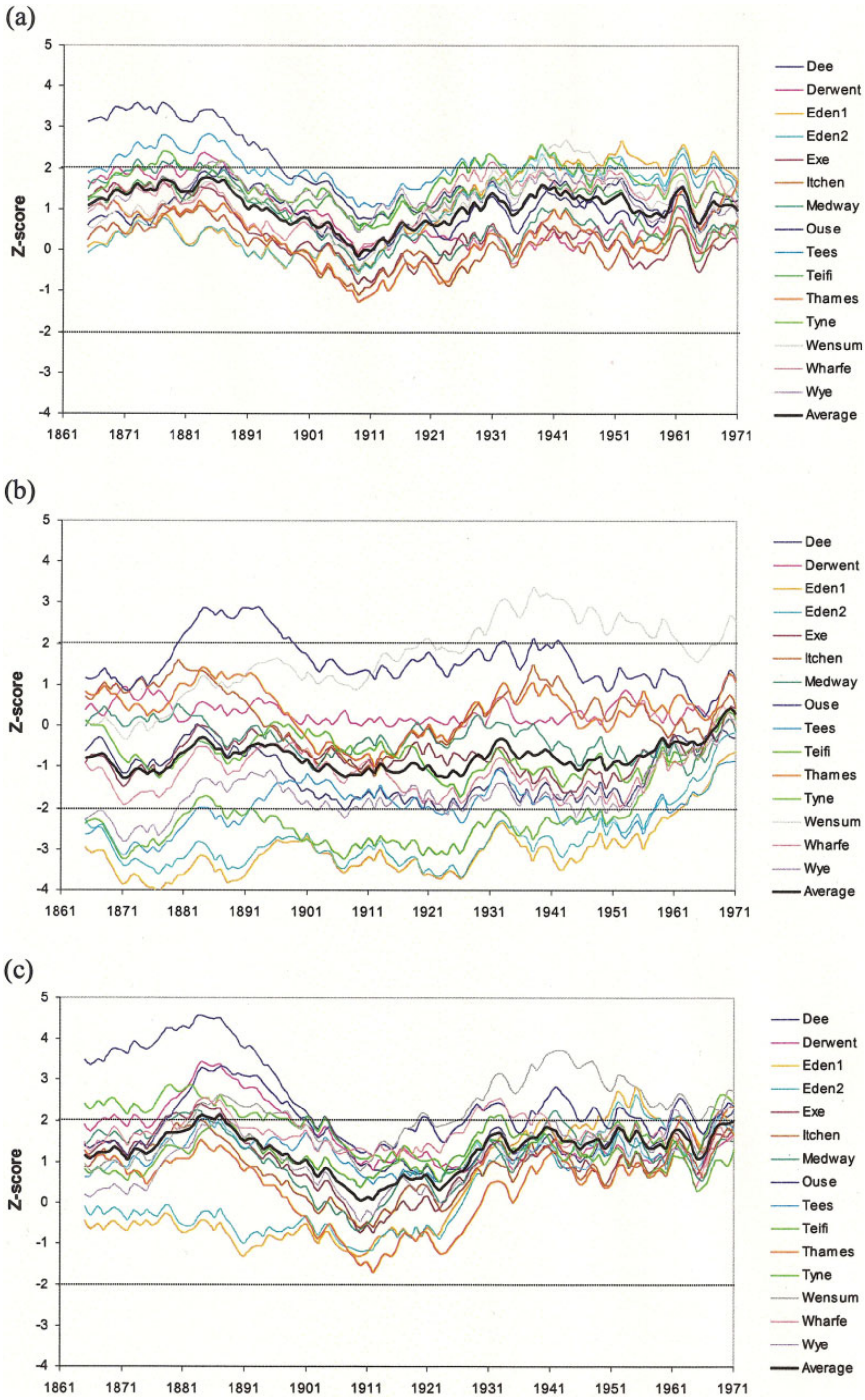

Figure 2. Results of a moving window trend analysis using long reconstructed records. Results show Mann-Kendall test for significant trends in (a) winter, (b) summer and (c) annual mean flows. The dashed horizontal lines show the critical value for the 95% confidence range. Trend statistics lying above (below) the line indicate significant increases (decreases) in flow since the corresponding date.
Source: Wilby (2006).

widely held perception that flood risk is increasing. In part, this has been fuelled by a succession of major flood events. The most notable widespread UK flood events of the last 15 years are listed in Table 2. Considerable scientific effort has been devoted to addressing whether these events are part of any trend towards increased flood frequency or magnitude – the literature on hydro-climatic change in the UK has predominantly been directed towards flooding.

A nationwide assessment of trends in river flooding was first carried out as part of research for the development of the *Flood Estimation Handbook* (*FEH*). Robson et al. (1998) and Robson (2002) pooled data for the 890 *FEH* stations – a significant proportion of the national network – in a national-scale trend analysis which considered flood magnitude (of Annual Maxima, AM) and frequency (Peaks-Over-Threshold, POTs) for 1941–1980 and 1941–1990 study periods. The studies found no significant trends for the whole national data set, nor for separate broad-scale regional and seasonal analyses.

The Benchmark network has since been used to examine evidence for climate-driven trends in flooding and high flows (Hannaford and Marsh, 2008) for the UK, for two study periods, 1959–2003 and 1969–2003. This study used indicators of flood magnitude (AM) and frequency (of POTs) based on HiFlows-UK (an update to the *FEH* data set used by Robson and co-workers) as well as indicators based on NRFA daily mean flows, including the magnitude of extended-duration high flows (10- and 30-day annual maximum flows) and high flow persistence (number of days above the Q10 threshold). The key finding was an increase in high flow magnitude and duration over both periods in the maritime-influenced upland areas of the north and west (Figure 3). A majority of POT frequency trends were also positive, and flood magnitude increased significantly at 20% of the sites, but, importantly, there were not always increases in peak flow at sites where high flows have become more frequent or prolonged. In contrast with the picture for the uplands, few compelling flood or high flow trends were found in the English lowlands. The recent seasonal analysis by Hannaford and Buys (2012) has added greater detail to this picture: winter high flow trends were steepest in the north and west, whereas autumn trends were steepest in central and southwest England, and eastern Scotland, reflecting the areas where autumn runoff has increased (see Figure 2). This study also found evidence for increasing high flows in some lowland catchments. Trends in spring and summer were more mixed, but some localized increases in high flows were observed in both seasons.

A number of regional studies of flood trends have been carried out and the results are in line with the findings presented at the UK scale. There has been a focus on upland areas and in general the findings all point to a tendency towards increasing high flows. Scotland has been one focal area: Black and Burns (2002) and Werrity (2002) found that the late 1980s and early 1990s contained a cluster of the highest floods on record for many catchments in western Scotland. The other regional focus has been on Wales and western England. Dixon et al. (2006) examined trends in flow regimes at 56 gauging stations in Wales and the English Midlands between 1962 and 2001, and found significant high flow trends in winter in the mountainous west, contrasting with the rain-shadowed east of the study region where high flow trends were more prevalent in autumn. Macdonald et al. (2010) found increases in POT frequency in 30 catchments across Wales (1973–2002) and also analysed records for changes in seasonality over time, although no marked shifts were found. Biggs and Atkinson (2011) focused on one large catchment, the Severn uplands (which primarily drains the mountains of mid-Wales), and found increases in annual and autumn extreme flows over the 1977–2006 period.

Table 2. Recent major flood events in the UK (modified and extended from Hannaford and Hall, 2012, with additional material on the 2012 floods from Parry et al., 2013).

Date	Areas affected	Hydrology	Impacts
Easter 1998	English Midlands	Persistent heavy rain falling on near-saturated catchments. 48-hour rainfall Return Periods (RPs) of 100 years. New period-of-record maximum flows in many large river catchments in central England.	Tens of thousands of people affected. Five fatalities. Insurance claims of £400–500 million. Prompted an independent government review, culminating in the Bye Report which identified lessons learned for flood risk management.
2000–2001	Much of England and Wales, with a focus on parts of Yorkshire, the Midlands and the southeast.	Protracted and widespread flooding resulting from the passage of numerous frontal systems, resulting in the most severe autumn–winter rainfall since 1947. High flow regimes of many rivers were redefined, with new maximum flows across much of England and Wales. RPs >150 years in some catchments.	Pervasive impacts on transport, agriculture and communities. Geomorphological impacts, e.g. landslides. Exceptional groundwater flooding in lowland England. Flood damage from the autumn alone estimated at £1 billion.
Summer 2007	Central and northern England	Wettest May–June on record (in a >240-year series) in England and Wales, causing record summer runoff. Prolonged frontal rainfall associated with several events with a large spatial footprint in June and July. Floods caused by heavy rainfall on catchments close to saturation, a very unusual occurrence in summer. New period-of-record maxima in >100 catchments. Some RPs >200 years.	Prompted the largest response by the emergency services since the Second World War. Over 55,000 homes and 6000 businesses flooded. Major damage to transport and infrastructure (including water and power supply). Associated with 14 fatalities and cost £3.2 billion. Prompted a major review of flood management strategies, the Pitt review.
November 2009	Northwest Britain, especially Cumbria	Intense and prolonged frontal rainfall, resulting from orographic uplift of warm, moist air. Rainfall caused rapid filling of lakes, resulting in lack of attenuation. New 24-hour rainfall record for the UK with an RP of >1800 years. New maximum flows in >20 catchments in Northwest England, highest RP of >2500 years.	Huge impact on communities in Cumbria, widespread flooding of homes and business, major infrastructure damage including destruction of bridges. Costs of damage £200 million. One fatality.

(continued)

Table 2. (continued)

Date	Areas affected	Hydrology	Impacts
2012	Much of England and Wales and parts of Scotland	An unprecedented hydrological transformation from drought in the first three months to flooding through much of the rest of the year. 2012 was the wettest year on record for England. Flooding was widespread across the UK and frequent from April to July, with further notable flooding again in November/ December. Many of the individual events were not especially severe, but the extent and duration of flooding was remarkable. Surface water flooding, fluvial flooding and groundwater flooding all occurred through the year.	Widespread floodplain inundations, but only 8000 properties flooded. Road and rail network severely affected by surface water flooding and landslides. Significant disruption to leisure and recreational activities throughout summer. Agricultural sector struggled to cope with sudden transformation from drought to floods; National Farmers Union estimated cost to rural Britain of wet weather in 2012 to be £1.3 billion. Rising and falling flood levels caused mostly negative ecological impacts.

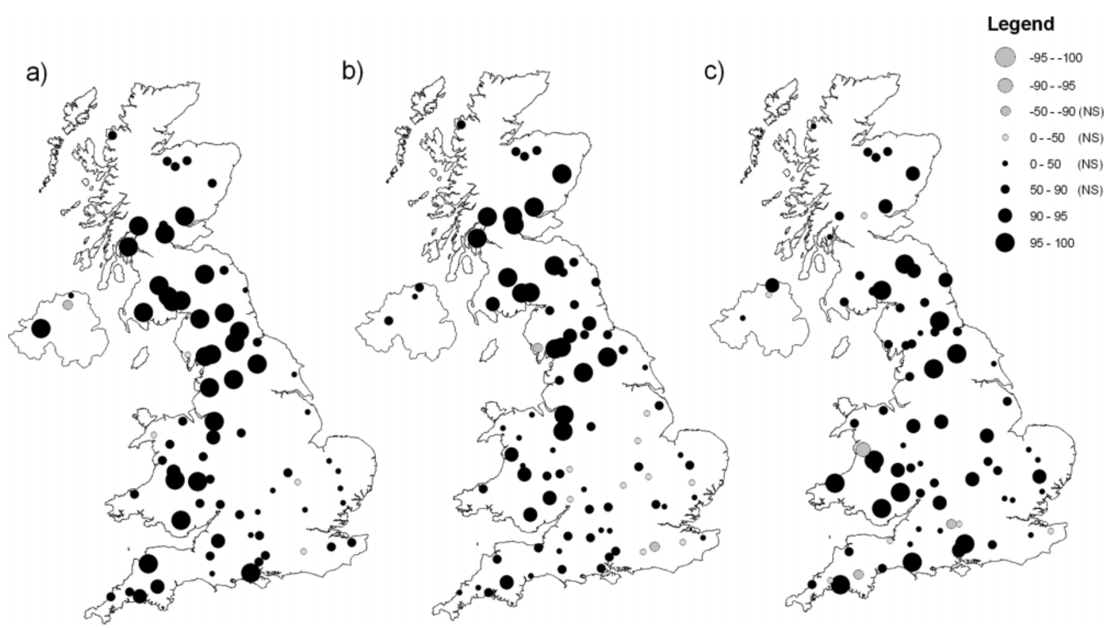

Figure 3. High flow trends in the UK Benchmark network: (a) 10-day maximum flow; (b) high flow duration, number of days above Q10 threshold; (c) instantaneous Annual Maximum flow. Legend shows trend index equivalent to p value of statistical significance test (95 = p > 0.05). Filled black circles are positive trends, filled grey circles negative.
Source: Adapted from Hannaford and Marsh (2008).

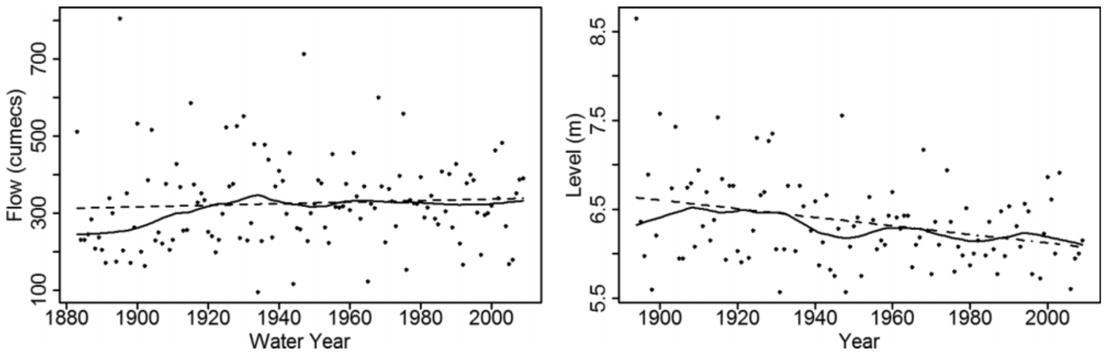

Figure 4. Long-term trends in flood magnitude at Teddington (Annual Maximum, left) and maximum lock levels (right) for the River Thames.
Source: Adapted from Marsh and Harvey (2012).

As with annual and seasonal river flows, studies of change in high flows and flooding have largely focused on the well-instrumented post-1960 period. National-scale assessments of trends over this period have typically sought to provide a long-term context using proxy records such as winter rainfall, and found substantial interannual variability and evidence of long-term climatic fluctuations (Robson et al., 1998). Hannaford and Marsh (2008) found that the increases in high flows from the 1960s to the early 2000s in upland Benchmark catchments in the north and west are not necessarily seen if analyses are extended, e.g. back to the 1930s for the river Wye and the Scottish Dee. However, dedicated long-term trend analyses of flooding are lacking, particularly for very long timescales, i.e. back to the turn of the 20th century or earlier. A detailed study of one of the longest continuous UK flood records (1883 -present), the Thames at Teddington (Marsh and Harvey, 2012), revealed no long-term change in flood magnitude, despite increases in temperature, winter rainfall and annual runoff (Figure 4). Maximum river levels have decreased over the period, reflecting the influence of river engineering and management practices.

The iconic Thames record is a rarity, and there are few published studies of long flood records available elsewhere in the UK. Other workers have attempted to address flood changes over much longer periods, extending back several centuries or more, by constructing chronologies of historical flood events. These chronologies assimilate a diverse range of sources, including documentary accounts, epigraphic evidence (such as flood marks on bridges), and palaeo-hydrological reconstruction (e.g. using floodplain sediments). Macdonald et al. (2006) and Macdonald and Black (2010) assembled chronologies extending from the 13th century for the Tay in Scotland and the Yorkshire Ouse, respectively, while Pattison and Lane (2012) developed a flood record extending back to 1770 for the Eden (northwest England). The fragmentary nature of these records, coupled with the inherent uncertainty associated with estimates for events which occurred hundreds of years ago, may limit their utility for statistical trend tests, but such chronologies provide a useful indication of the magnitude of flood events in the pre-instrumental record. In many cases, these events greatly exceed the envelope of recent flood behaviour (e.g. Macdonald, 2012; Macdonald and Black, 2010). One of the unifying themes to arise from such studies is the prevalence of interdecadal variability in flood records – in particular, the presence of distinct 'flood rich' and 'flood poor' periods. Similar conclusions have been reached using long (extending back to the late 1800s) flood occurrence records reconstructed from atmospheric circulation patterns, which have been produced at a regional scale in the UK (Wilby and Quinn, 2013).

V Low flows and hydrological drought indicators

Low flows have generally received less attention in studies of hydrological change. Hannaford and Marsh (2006) carried out a national-scale assessment of trends in low flows, using the Benchmark network. They analysed indicators of low flow duration (number of days below Q90) and magnitude (7- and 30-day annual minima) and concluded there was little compelling evidence for change over the 1960s to early 2000s. No significant trends were found across the English lowlands, although a tendency for weak decreasing trends was noted. Regional studies also found little evidence for low flow changes (Dixon et al., 2006; Werrity, 2002) in Scotland and Wales, over broadly similar timescales.

Recent studies have found a similar lack of evidence for low flow trends. Marsh and Dixon (2012) analysed Q95 trends for the national outflow series and also found no significant trends, with weak increases in Q95 outflows for Scotland, Wales and England as a whole, and a weak tendency towards decreasing trends in the English lowlands (see Table 1). Interestingly, Hannaford and Buys (2012) found that winter Q95 flows have decreased over the 1969–2008 period in parts of western Britain which have seen overall runoff increases and increased high flows – thus suggesting a greater range of flows. These authors found limited evidence for decreases in low flows in other seasons: moderate decreases in spring (associated with a decreasing seasonal mean) but few observed decreases in summer low flows, and a lack of spatial coherence in patterns of change. These results appear inconsistent with the findings of Stahl et al. (2010), who found decreases in low flow, and summer flow, in 36 UK benchmark catchments (as part of a wider European study) over the 1962–2004 period. This serves to illustrate the importance of study period, as this study began in the wetter early 1960s and ended with the 2003 drought (and emerging drought in 2004) whereas the study of Hannaford and Buys (2012) ends after the wet summers of 2007 and 2008. Sensitivity to study period underlines that published trends are generally weak (Hannaford and Marsh, 2006). Overall, there seems to be little evidence of any strong decrease in low flows since the 1960s.

Despite a general lack of trends in low flows, the recent past has seen a number of high-profile drought events with significant societal impacts, e.g. 2004 to 2006 (Marsh et al., 2007) and 2010 to early 2012 (Kendon et al., 2013). Beyond the low flow trend studies above, there have been relatively few attempts to examine whether these events are part of a long-term trend in hydrological drought severity or magnitude. Drought is a complex phenomenon, and cannot just be characterized by low river flow time series. There have been a number of studies which address changes in meteorological drought indicators (e.g. Burke and Brown, 2010), which are not considered in detail here given the focus of this paper on river flows. A brief summary is given of studies which have examined changes in indicators of river flow (hydrological) drought, often in tandem with other variables such as precipitation.

Recently published drought catalogues (Hannaford et al., 2011; Lloyd-Hughes et al., 2012) show regional-scale hydrological and meteorological droughts for five UK regions (northwest, northeast, southwest and southeast, with the latter being subdivided into groundwater and non-groundwater catchments), using indicators of river flow and precipitation deficit. The river flow catalogues clearly show the major droughts of the 1990s, although there is no obvious trend in drought occurrence: rather, a contrast between the drought-poor (1980s, late 1960s) and drought-rich periods (1990s, 1970s), as shown by the example in Figure 5. Interestingly, the meteorological catalogue shows many significant droughts through the 20th century, which are of similar (or greater) duration and intensity as those of the recent past. Evidence from reconstructed flow records supports this observation: Jones and Lister (1998) found evidence for many historical droughts which were more severe than those of the 1990s, which correspond to many of the precipitation droughts shown in the catalogues (e.g. 1921/1922; 1933/1934), but also including a number of severe droughts in the late 19th century. Watts et al. (2012) extended a reconstructed flow series back to 1803 for the Ely Ouse (East Anglia) to identify the worst-observed historical multi-year droughts, and found that the majority of the longest droughts were in the 19th century.

A multi-indicator assessment of major historical droughts in England and Wales was carried out by Marsh et al. (2007). This study collated reconstructed runoff, long rainfall and groundwater records, as well as anecdotal reports (e.g. from the British Hydrological Society Chronology of hydrological events). The list of major droughts compiled is shown in Table 3. This review, along with other long-term hydrological drought studies, identifies a general tendency for droughts to cluster together; in particular, for multi-year droughts to occur in succession, interspersed with relatively drought-free periods. The 'long drought' period from 1890 to 1910 is a particular example of such a run of dry episodes. Overall, however, Marsh et al. (2007) found no compelling evidence of any long-term trends towards increased drought severity in England and Wales, and underlined the importance of interdecadal variability as the primary feature of historical drought patterns. The causes of this variability, however, remain poorly understood.

VI Discussion: attribution of change and consistency with future projections

Merz et al. (2012) argue that trend attribution studies should adopt three core ingredients: a proof of consistency (with a particular hypothesis, e.g. driven by climate); a proof of inconsistency (to rule out other causes, e.g. land use); and a statement of uncertainty. These authors go on to argue that this is rarely the case in existing research, and that most studies rely on 'soft' attribution and speculation, rather than 'hard' attribution based on the above framework. The UK is no exception, and attribution of observed trends is generally rather indirect, partly as a result of the challenges presented by short river flow records. The use of Benchmark catchments represents an attempt to capture a proof of inconsistency, i.e. that trends are not consistent with direct disturbances such as abstractions or effluent returns, which have been controlled in the specification of the network. Hence, most of the reported patterns of change are likely to be climate-driven; whether they are driven by anthropogenic forcing, natural variability or, as is intuitively most likely, a combination of both, is a more vexed question.

There are certainly some parallels between observed patterns of change in runoff and high flows and projections of future climate change impacts on seasonal rainfall (e.g. Murphy et al., 2009), extreme rainfall (e.g. Ekstrom et al., 2005) and river flows (e.g. Arnell, 2011; Kay and Jones, 2012), which suggest increases may be greatest in the winter half-year and in upland areas of the UK. However, the regional patterns also appear consistent with changes in large-scale atmospheric circulation, in particular the North Atlantic Oscillation (NAO), the dominant mode of climatic variability in the UK. Recent studies have found strong relationships between the NAO and winter and annual runoff (e.g. Burt and Howden, 2013; Laizé and Hannah, 2010) and high flows (Biggs and

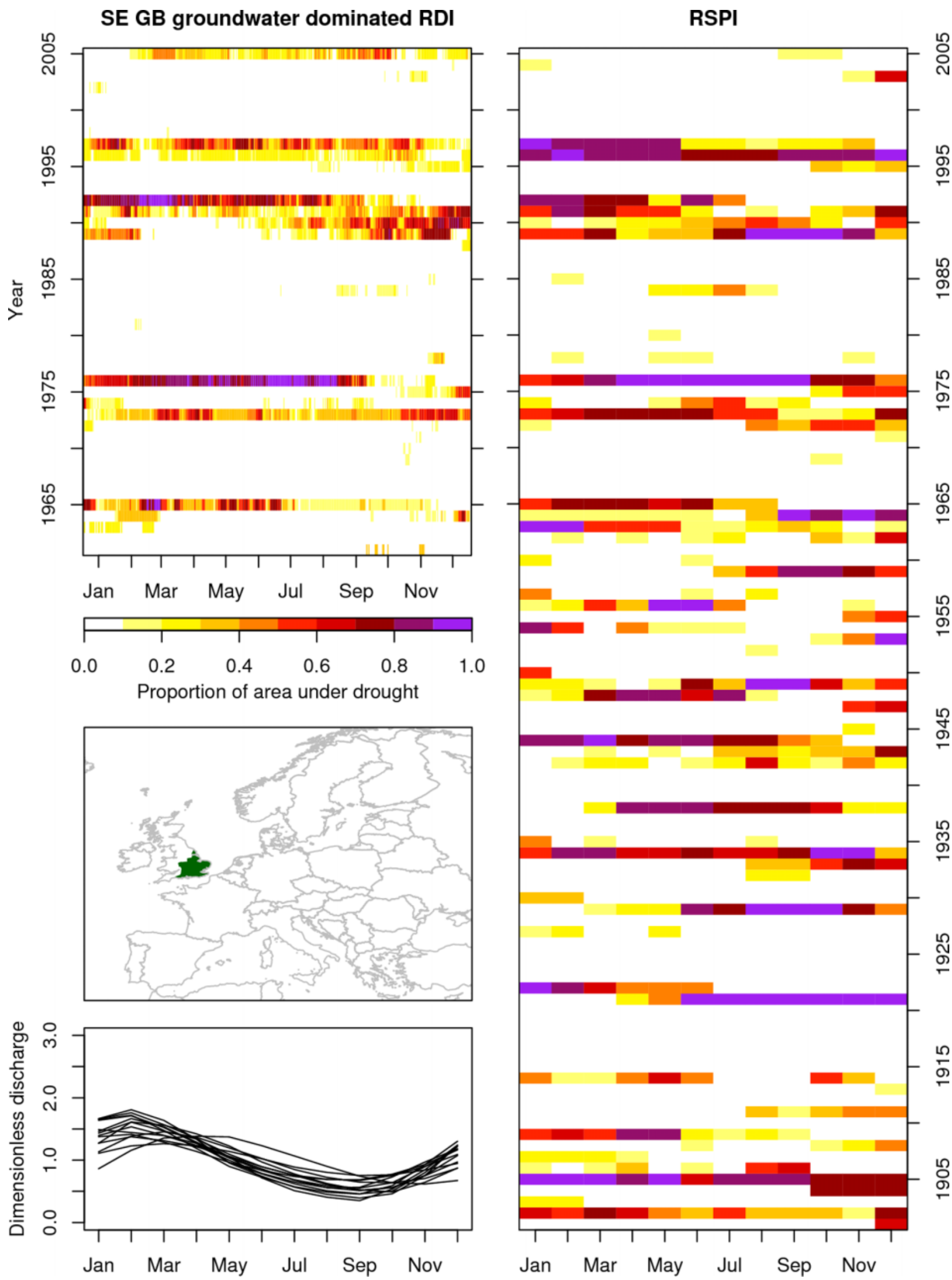

Figure 5. Example Drought Catalogue page for southeast England (groundwater dominated catchments). The RDI (Regional Deficiency Index) shows regional river flow droughts, while the RSPI (Regional Standardized Precipitation Index) shows meteorological droughts. Full details on the methodology and drought catalogues for all five UK regions can be found in Lloyd-Hughes et al. (2012).

Table 3. Major droughts in England and Wales, 1800–2007 (Marsh et al., 2007).

Year	Duration	Comments
1854–1860	Long drought	Major long duration drought. Sequence of dry winters in both the lowlands (seven in succession at Oxford) and northern England. Major and sustained groundwater impact.
1887/88	Late winter 1887 to summer 1888	Major drought. High-ranking rainfall deficiencies across a range of timeframes. Very widespread (across most of British Isles). Extremely dry 5-month sequence in 1887. Primarily a surface water drought – severe in western Britain (including northwest).
1890–1909	Long drought	Major drought – long duration (with some very wet interludes, 1903 especially). Initiated by a sequence of notably dry winters. Latter half of the period features a cluster of dry winters. Major and sustained groundwater impact, with significant water supply problems. Most severe phases: 1893, 1899, 1902, 1905. Merits separate investigation.
1921–22	Autumn 1920 to early 1922	Major drought. Second lowest 6-month and third lowest 12-month rainfall totals for England and Wales. Very severe across much of England and Wales (including Anglia and southeast; parts of Kent reported <50% rainfall for the year); episodic in northwest England.
1933/34	Autumn 1932 to autumn 1934	Major drought. Intense across southern Britain. Severe surface water impacts in 1933 followed by severe groundwater impacts in 1934, when southern England heavily stressed (less severe in the more northerly, less responsive, chalk outcrops).
1959	Feb to Nov	Major drought. Intense 3-season drought – most severe in eastern, central and northeastern England. Significant spatial variation in intensity. Modest groundwater impact.
1976	May 1975 to Aug 1976	Major drought. Lowest 16-month rainfall in E&W series (from 1766). Extreme in summer 1976. Benchmark drought across much of England and Wales – particularly the lowlands; lowest flows on record for the majority of British rivers. Severe impact on surface water and groundwater resources.
1990–92	Spring 1990 to summer 1992	Major drought. Widespread and protracted rainfall deficiencies – reflected in exceptionally low groundwater levels (in summer 1992, overall groundwater resources for England and Wales probably at their lowest for at least 90 years). Intense phase in the summer of 1990 in southern and eastern England. Exceptionally low winter flows in 1991/1992.
1995–97	Spring 1995 to summer 1997	Major drought. Third lowest 18-month rainfall total for England and Wales (1800–2002). Long-duration drought with intense episodes (affecting eastern Britain in hot summer of 1995). Initial surface water stress, then very depressed groundwater levels and much diminished lowland stream network.

Atkinson, 2011; Hannaford and Marsh, 2008) in northern and western areas. This body of research suggests the wetter winters – and associated river flow patterns – observed in upland areas are influenced by changes in westerly airflows linked to multi-decadal variability in the NAO. This does not rule out climate change having an underlying effect, as many modelling studies suggest recent behaviour of the NAO is itself influenced by anthropogenic warming (e.g. Dong et al., 2011). The NAO is also just one of numerous interlinked drivers of North

Atlantic climate variability that act over a range of different spatial and temporal scales. Recent studies (Lavers et al. 2011; 2012) have demonstrated the importance of Atmospheric Rivers (ARs), narrow bands along which a large flux of moisture is transported from the subtropics to mid-latitudes, causing winter flooding and extreme rainfall in the north and west of the UK. ARs are expected to become more frequent in the future under anthropogenic warming (Lavers et al., 2012), but so far there has been no analysis of whether there is any anthropogenic contribution to the prevalence of ARs in the observed record.

In comparison with evidence for increases in winter and high flows in upland locations, there is very limited compelling evidence for any decrease in low flows or summer runoff. Where declining low flow or summer flow trends are found, they are sensitive to study period, and the direction and magnitude of change can be altered by clusters of wet of dry years; evidence from long records also shows limited evidence for change. This lack of trends is, in itself, an important result given favoured climate change projections. On the basis of the review of evidence presented here, there is no regionally coherent decrease in summer flows or low flows, seemingly at odds with model-based studies projecting decreased summer flows by the '2020s' (a 30-year period covering 2011–2040) relative to a 1961–1990 baseline (von Christierson et al., 2012). The short records and high spatial variability in trend responses mean that a lack of apparent trend in summer flows or low flows cannot be taken to mean that anthropogenic forcing is not having some underlying effect; but the lack of coherent observed change in summer contrasts with the outcomes of model-based studies. Summer decreases are one of the more consistent results from future projection studies, albeit with a wide range of possible magnitudes (Prudhomme et al., 2012; von Christierson et al., 2012).

The very mixed pattern in summer river flows is perhaps not surprising given the sequence of wet summers witnessed from 2007 to 2012 – two of which were associated with widespread flooding (Table 2) – which stands in contrast to the general expectation of drier summers in future. The cause of these anomalous summers is a major focus for ongoing investigation: sea-surface temperature anomalies associated with the recent warm phase of the Atlantic Multidecadal Oscillation (AMO) have been associated with wetter summers in northern Europe (Dong et al., 2013; Sutton and Dong, 2012). Other researchers have claimed that sea-ice declines may also play a role in wet summers in Europe (Francis and Vavrus, 2012; Screen, 2013). However, this area is hotly debated and there is currently limited consensus (e.g. Tett et al., 2013) on the relative roles of these drivers. A key research priority is to understand how these influence river flows, particularly in relation to recent extremes and the long-term patterns of interdecadal variability which confound trend detection. While there has been extensive work on the influence of the NAO in winter, less attention has been focused on other seasons and other drivers. The recent observed decreases in spring river flow warrant attention as similar patterns of variability have been found elsewhere in western Europe (France, Giuntoli et al., 2013; Ireland, Murphy et al., 2013).

The above discussion has largely focused on the attribution question by making comparisons with future projections ('associative') rather than direct, statistical attribution. In theory, a more robust approach is to use formal attribution methods such as optimal fingerprinting and related methods that use large ensembles to simulate 'natural' and 'anthropogenic' climates. Such methods have been widely applied for climate variables (see, for example, the review of Stott et al., 2010) but have only recently been applied to hydrological data. Pall et al. (2011) estimated that anthropogenic warming increased the risk of the autumn 2000 floods by a factor of 2.5 (i.e. the risk of the event would have been 40% less in the absence of emissions). This is an emerging area of science, and it remains to be seen whether such approaches can be applied to long-term river flow patterns at the catchment scale. A follow-up study on the same 2000 flood event found the fraction of risk attributable to warming varied widely between catchments with different properties (Kay et al., 2011).

VII Concluding remarks

The anticipated influence of climate change on the hydrological cycle has motivated a considerable research effort focused on hydro-climatic change in the UK. Changes can be found in river flow regimes over the last 40–50 years – particularly for the winter half-year, and in the western uplands especially – but there is generally little evidence for any long-term trends in river flow, and no compelling trends in flooding or drought. There is currently no strong evidence for anthropogenic warming influences on river flows in the UK: some changes have parallels with expectations of future change under anthropogenic warming (e.g. increases in winter flows), but these cannot be attributed to climate change due to the confounding effects of interdecadal variability. There is no evidence of any pronounced decreases in summer flows or low flows, as projected by most future climate studies.

Wilby et al. (2008) argue that mismatches between model outputs and results from observational studies are sometimes regarded as a ‘conceptual controversy’ but that they largely reflect the inherent differences and limitations of the two approaches. Modelling studies are subject to large uncertainties, while observational studies are subject to limitations in the data and methodologies used. In particular, the low signal-to-noise ratios seen in hydro-climatic time series may mean changes are not statistically detectable for many decades in the UK (Wilby, 2006). Changes may be influential from a water management perspective long before they are statistically detectable. Despite the lack of convincing evidence for any long-term trend in river flows, the recent past has certainly seen notable hydrological volatility. The 2010–2012 drought and subsequent flooding throughout 2012 (Kendon et al., 2013; Parry et al., 2013), along with the major flooding associated with the severe storms of the winter of 2013/2014 (Slingo et al., 2014), have underlined the continuing vulnerability of the UK to river flow extremes. With such wide uncertainties in future projections – with obvious implications for adaptation decisions – observed data sets of historic river flow will assume critical importance in our efforts to understand and manage changing river flow extremes in future. The UK has been at the forefront of efforts to ensure observational data sets are suitable, and widely available, for hydro-climatic detection, with the UK Benchmark network representing an internationally significant example of a reference hydrometric network (Burn et al., 2012; Whitfield et al., 2012).

Although much work has been done on historic change, there are many significant gaps in research. The spatial heterogeneity of observed trends (in the English lowlands especially) warrants detailed investigation, as catchment properties can modulate climate variability (Laize et al. 2010; Lavers et al. 2010) and will play a significant part in influencing how climate change influences future flow regimes (Prudhomme et al., 2013). Furthermore, direct human disturbances on river flows may be as important as climate variability in dictating observed patterns of river flow change. The designation of the Benchmark network attempted to remove the effect of major influences, but this is easier to undertake for large abstractions and impoundments, much less so for more subtle impacts such as land-use and land-cover change. Moreover, Benchmark catchments are generally (but not exclusively) small, headwater sites where changes in flow regimes may have less impact on society; there remains a need to fully characterize past trends in downstream, heavily modified catchments where changes may be most influential and where separating the relative roles of human and natural drivers will pose great scientific challenges, necessitating novel data/ model integration studies (e.g. Harrigan et al., 2013). It is also important to take account of the scale divide when extrapolating from small headwater reference catchments to downstream locations (Whitfield et al., 2012), underlining the importance of combining trend assessments from Benchmark catchments alongside parallel analyses from wider regions (as in the national outflow series described here).

Hydro-climatic trend testing in the UK (as elsewhere; Burn et al., 2012; Merz et al., 2012) has largely focused on monotonic changes in fixed periods, the interpretation of which is inevitably hampered by interdecadal variability (Hannaford et al., 2013). One of the biggest priorities for research should be understanding the drivers of interdecadal variability in river flows. To facilitate such research there is an ongoing need for efforts to ensure the preservation and stewardship of long records (including rescue and recovery, e.g. Bayliss et al., 2004), as well as reconstruction using hydrological modelling and historical proxy data (e.g. Jones et al., 2006; Macdonald and Black, 2010; Wilby and Quinn, 2013).

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