# A climate change report card for water

## Working Technical Paper

# 2. Observed long-term changes in UK river flow patterns: a review

**Jamie Hannaford**

**National River Flow Archive**

**Centre for Ecology and Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB**

# Observed long-term changes in UK river flow patterns: a review


**SUMMARY OF MAIN FINDINGS**

- The UK has a very dense network of river flow monitoring sites, which provides a strong foundation for detecting long-term changes in flow. However, human disturbances (e.g. abstractions) are pervasive, so caution is required in interpreting trends. Networks of near-natural catchments should be used where possible.

- The majority of river flow records are from post-1960; longer records are rare and often of poorer quality, but provide a useful guide to runoff patterns over long timescales.

- Annual runoff has increased since the 1960s in Scotland, Wales and parts of northern and western England; in contrast, no pronounced changes have occurred in the lowlands of southeast England.

- Winter runoff has increased since the 1960s, especially in the upland, strongly maritime-influenced parts of the UK. Longer records suggest that winter runoff has increased in some northern and western catchments over the twentieth century, but the trends are generally weaker than for the post-1960 period.

- Spring runoff has increased in northern and western areas, and decreased across the English lowlands since the 1960s, but trends were fairly weak. The post-1960s decreases are not representative of longer timescales; many long records show increases in spring runoff from the 1930s/1940s to present.

- Summer runoff patterns are spatially heterogeneous, and results from different studies disagree (primarily due to different study periods). There is limited evidence for any long-term change in summer runoff; a tendency towards decreasing summer runoff is easily reversed by a few wet years. Long records show limited evidence for pronounced changes in summer flow.

- Autumn runoff has increased since the 1960s, notably so in some areas of central and southwest England and Wales, and eastern Scotland. Limited evidence from longer records indicates that autumn runoff has increased over longer timescales.

- In northern and western localities, pronounced increases in indicators of the duration and magnitude of high flows (e.g. 10-day average flows, Q5 flows) have occurred since the 1960s. Long records show that post-1960 increases in high flows are steeper than those found over longer periods. Whilst high flows have increased in many catchments, the evidence for trends in flood magnitude is generally less compelling. Long flood records

generally show strong inter-decadal variability, with marked fluctuations between flood rich and flood poor periods.

- Generally, rather mixed patterns were observed in low flows, with the strength and direction of trends varying strongly between different study periods. There is no strong or consistent evidence for decreases in low flows. Assessing longer-term change is rendered difficult by the unsuitability of long hydrometric records for low flows.

- Similarly, there is no strong evidence for changes in the characteristics of hydrological droughts in published studies – recent droughts are not as severe as many historical droughts, particularly those occurring in the nineteenth century, and longer records display a tendency for droughts to cluster together, as with flood series.

- There is some consistency between river flow trends and some observed climatic trends (e.g. post-1960 increases in winter and autumn rainfall and runoff) but also some important differences (particularly in spring and summer). These differences may reflect other factors such as changing evapotranspiration and partitioning between rain and snow. The role of these factors in driving observed flow changes remains poorly understood and remains an important research gap.

- Increased winter runoff and high flows in northern and western areas since the 1960s is likely to reflect changes in the North Atlantic Oscillation (NAO). An extensive body of research has documented the role of the NAO in driving rainfall and river flows. However, the role of the NAO (along with other atmospheric circulation drivers) in driving long-term multi-decadal variability in river flows is a knowledge gap.

- The limited evidence for changes in river flow must be set against a background of strong evidence for increasing temperatures attributable to anthropogenic warming. However, attributing specific streamflow trends to anthropogenic warming is currently not possible. Some trends (e.g. winter runoff and high flow increases) are consistent with future climate changes but also with NAO-driven variability. The lack of summer trends or low flow trends is in apparent contradiction to expectations of future climate change. However, such differences do not rule out climate change effects, and point to an ongoing need for research aiming to reconcile observed trends and model-based projections.

## 1. Aims and Scope

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. This paper necessarily focuses on climate-driven changes in flow, as opposed to capturing changes caused by human influences such as water management practices (e.g. abstraction, discharges, impoundments) or changes in land-use or land management. The paper reviews evidence for changes through the twentieth century, up to the present (2012). However, some consideration is also given to changes earlier than 1900. The focus of the work is on the UK, although a section briefly considers the wider European context.

The paper begins with some background on the mechanisms through which climate change may influence river flows, and a description of the data and methods which 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, and river flow trends at the wider European scale. Attribution of observed trends is then discussed, focusing on consistency with observed climate changes, and addressing whether changes can be attributed to anthropogenic warming. Finally, an assessment of confidence in observed changes is made, and knowledge gaps are listed.

## 2. Background

### 2.1 Climate change and impacts on river flows

Anthropogenic global warming is likely to intensify the hydrological cycle: increased temperatures would be expected to increase evaporation, and a warmer atmosphere can hold more moisture, leading to enhanced precipitation (Huntington, 2006). However, climate change will also alter atmospheric circulation, so changing precipitation patterns are unlikely to be spatially uniform over large areas of the earth's surface. Furthermore, climate change is expected to result in greater changes to the extremes of weather (IPCC, 2007). Giorgi et al. (2012) propose that a ubiquitous signature of future anthropogenic warming will be enhanced hydroclimatic intensity, characterised by increases in precipitation intensity, dry spell length and, in many locations, a combination of both.

It is natural to assume that a changing climate will lead to modified river flow regimes. Changes in the water or energy balance could modify the magnitude, timing and seasonal distribution of river flows, whilst more intense rainfall could increase flood severity. However, there are considerable uncertainties in modelling projections for climate change (e.g. Wilby et al. 2008) and there are gaps in our understanding of how climate change (whether observed historic or projected future) influences river systems. There is a complex, non-linear chain from increasing temperatures, through related changes in climatic characteristics, 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 and to provide "ground truth" for scenario-based model outputs.

River flow regimes represent the integrated response of all hydrometeorological processes acting upon a catchment, and they therefore provide a more direct assessment of water resources than characterisations based on precipitation. Furthermore, it is through changing 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, and a proliferation of studies which attempt to detect river flow trends and assess whether they are influenced by climatic change. A recent review identified 128 studies of long-term trends in river flow regimes (Burn et al. 2012). A majority of studies are national or sub-national scale, but some have attempted to examine trends at the continental (e.g. Stahl et al. 2010) or global scale (e.g. Dai et al. 2009). In the UK, river flow change has been a focus of a substantial research effort over the last two decades. There are few parallels, internationally, to the quantity and breadth of studies (particularly relative to the size of the area under consideration) which form the basis of the following review.

### 2.2 The data resource: the UK Gauging Station Network

The UK has an exceptionally dense gauging station network by international standards, which is a necessary response to its diversity, in terms of climate, geology, terrain, and patterns of settlement and water utilisation. The principal archive of hydrometric data for the UK is the National River Flow Archive (NRFA), which holds data for around 1500 gauging stations. These data are collected by the measuring agencies (Environment Agency, Scottish Environment Protection Agency and Rivers Agency of Northern Ireland) and passed to the NRFA for long-term stewardship. A separate archive (HiFlows-UK) exists for flood peak data (also derived from the measuring agencies), which contains peak flows for over 1000 stations.

NRFA: http://www.ceh.ac.uk/data/nrfa/index.html

HiFlows-UK: http://www.environment-agency.gov.uk/hiflows/91727.aspx

From the perspective of hydrological change detection, the UK is blessed with an extremely rich information resource. However, this 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 (with only two continuous records extending from the 19th century to the present), and the quality and homogeneity of longer flow records is typically compromised by changes in gauging practices. The UK is densely populated, and therefore human disturbances on runoff patterns are pervasive. Artificial influences (for example, changing abstraction and discharge patterns) can lead to spurious trends which bear little relation to climate variability. For example, Figure 1 illustrates a time series which shows a strong downward trend for a Chalk catchment in the English Lowlands. This trend corresponds with a period of substantial growth in groundwater abstraction, which eventually led to the identification of the Ver as an over-abstracted river and the introduction of an Alleviation of Low Flows scheme (Clayton et al. 2008). Finally, whilst hydrometric data quality in the UK is extremely high by international standards, data quality constraints inevitably impinge on the utility of many gauged time series – 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, 2010).

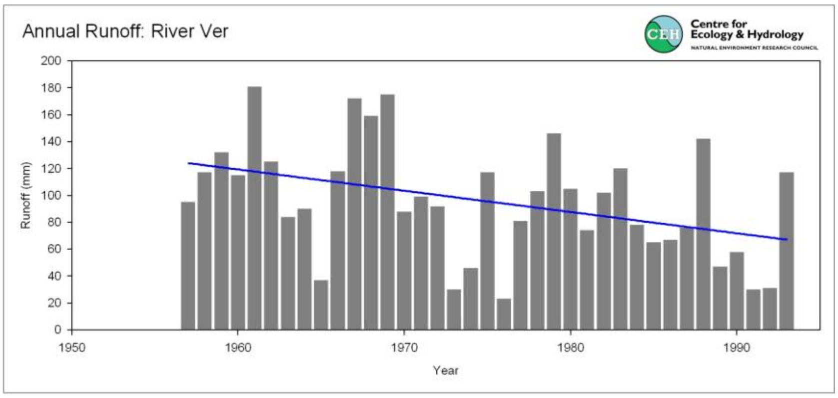


**Figure 1: An example of a trend caused by artificial disturbances to a flow regime. The decreasing annual runoff trend for the Ver at Hansteads is primarily driven by a significant increase in groundwater abstraction over the period shown in this plot**

As a result of these confounding factors, comparatively few of the c.1400 NRFA gauging stations are suitable for detecting long-term trends, and caution is required in interpreting the results of any assessment of river flow change. In order to overcome some of these obstacles, several data initiatives have sought to strengthen our capability to detect climate-driven trends. As these are referred to throughout this review, a brief description is given below.

- The UK Benchmark Network: a subset of around 130 stations on the NRFA, designated to allow climate-driven trends to be distinguished from direct anthropogenic impacts. The Benchmark network represents an attempt to formulate a Reference Hydrometric Network (RHN) for the UK. Benchmark catchments have near-natural flow regimes, and are gauged by stations which produce good quality data; their designation is described by Bradford and Marsh (2003). There is a growing international recognition of the importance of RHNs in efforts to detect climate change patterns, and similar networks exist in the USA, Canada, and a number of European countries (see Burn et al. 2012 for reviews of RHNs).
- Reconstructed runoff series: a set of 15 long, monthly river records for catchments in England and Wales which extend back to 1895, derived by Jones and Lister (1998) and updated to 2002 by Jones et al. (2006). These records are reconstructed using a rainfall-runoff model driven by good quality, long precipitation records, which, in comparison with river flow records, are relatively numerous in the UK.
- National and Regional runoff series: records of total outflows for the various constituent countries of the UK (England, Wales, Scotland, Northern Ireland) and sub-regions (the English Lowlands). These series are derived by aggregating flows from major river basins, and applying a correction factor (based on hydrological modelling) to the ungauged areas. The datasets are described by Marsh and Dixon (2012) and Marsh et al. (in preparation).

### 2.3 Methodologies for change detection

Analyses of long-term change in hydro-climatic time series typically use some form of statistical methodology, such as linear regression or the Mann-Kendall test, to test for non-stationarity. The methods employed are not described in detail here – the reader is referred to general reviews of hydro-climatic change detection methods (e.g. Kundzewicz and Robson, 2004). However, it is important to note that such methods have inherent limitations. Trend testing is therefore a controversial area, and the literature abounds with discussion on the appropriateness (or otherwise) of hydro-climatic trend tests (e.g. Svensson et al. 2006; Clark, 2010; Hirsch, 2010; Merz et al. 2012; Burn et al. 2012). The detailed statistical issues are not addressed here; rather, 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 well short of this. It could be argued that even 50 years is too short: numerous authors have cautioned against using linear trends over a fixed period, as a trend in a given period may represent part of a longer-term pattern of variability (e.g. part of some cyclical process; Chen and Grasby, 2008). The problematic nature of short-term trend tests is illustrated via a UK example in Figure 2, which shows trends fitted to short periods in the river Dee (Scotland) record: depending on the period selected, both increasing and decreasing trends can be observed, whilst the smoothing line shows that the dominant pattern is fluctuations on decadal scale, with distinct periods of higher- or lower- than average conditions (e.g. the 1990s vs the 1960s). There is a growing consensus that the assumptions of statistical trend tests are violated by the presence of such long-term persistence in hydrological time series (e.g. Cohn and Lins, 2005). Other authors have also cautioned against the misuse of statistical tests, and placing undue weight on arbitrary concepts of significance, such as 95% significance thresholds (Clarke et al. 2010). Certainly, random variations are a major confounding factor: 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 trends are not *detectable*, in a formal statistical sense, but may still be exerting an effect which is relevant for water management.

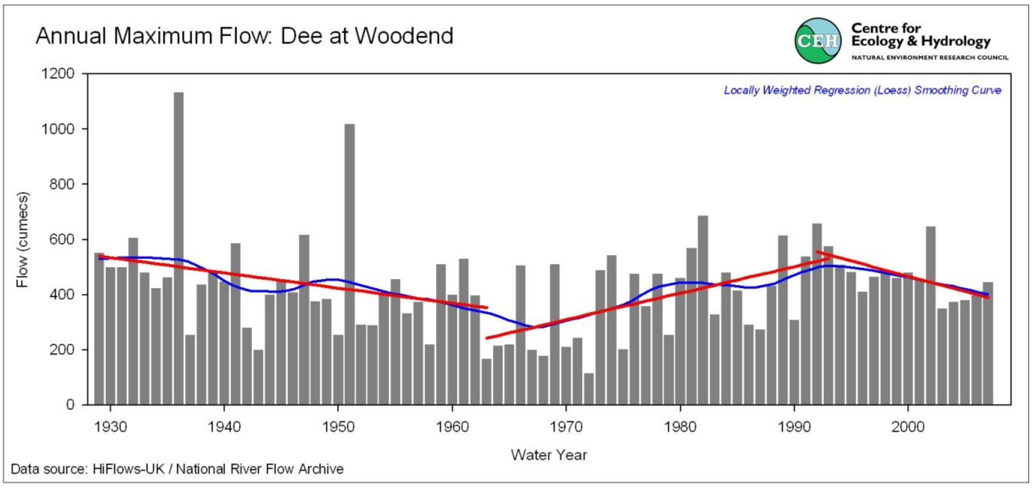


**Figure 2: The importance of study period and the problem of short records. Trends fitted to short periods can show opposing direction and substantially different magnitude. Fluctuations at an interdecadal scale are shown by the LOESS smoothing line.**

The combination of short records, methodological constraints and data quality issues is a real obstacle to the attribution of trends. Data quality limitations can be overcome to a certain extent, through judicious selection of catchments (i.e. using an RHN such as Benchmark catchments). Nevertheless, the methodological constraints, particularly the confounding influence of multi-decadal variability, are much more difficult to overcome, and as such 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. This is revisited in relation to the UK evidence base in Section 3.5.

# 3. Review of the evidence

## 3.1 Annual and Seasonal Runoff

Annual and seasonal runoff are arguably the most simple indicators of overall water availability, and provide a good starting point for assessing hydrological change. Marsh and Dixon (2012) and Marsh et al. (in preparation) recently conducted an analysis of trends in the national runoff series, which thus provide a foundation for assessments of changes in runoff at very broad scales for the UK (Table 1). Runoff increased over the 50 year period 1961 – 2011 for Scotland, Wales, and Great Britain as a whole. However, only the trend for Scotland was found to be 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). The latter results were consistent with the national runoff analysis: 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 benchmark catchments anywhere in central, southern or eastern England.

**Table 1 Changes in various flow indicators for the total outflows series, 1961 – 2010 (Marsh et al. submitted). Values show the % change over the course of the record. 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 |

Whilst annual runoff gives an indication of overall water availability, it masks within-year variability: climatic change may result in changes in seasonality, and changes in different seasons could cancel each other out at the annual scale. As the individual seasons can be important for different aspects of water management, it is also important to establish whether there have been any changes at the seasonal scale. Seasonal runoff trends were examined for the national outflow series: strong increases were observed for winter (although this was only significant for Scotland), weak 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 3 (slope magnitude indicates strength of trend). Once again, the strongest increases were seen for the winter half-year: winter runoff increased in upland, northern catchments, whilst autumn runoff increased across much of the UK. Spring runoff decreased across lowland England, although this was weak in many catchments, whilst summer presented an extremely mixed picture, with increases in the north and west and no regionally coherent patterns in the English lowlands.

The findings from these national-scale analyses are supported by a limited number of more localised, but more detailed, trend analyses from various UK regions. Dixon et al. (2006) analysed trends in Wales and the west Midlands, and reported increasing runoff in some catchments in Wales over the 1962 – 2001 period, but there were few significant seasonal trends (over a shorter period from 1977). Werritty (2002) analysed data for 38 stations in Scotland (1970 – 1996) and found increasing annual runoff at 33 (of which 12 were significant). Despite the differing study periods, results from these studies are consistent with the national-scale assessments.

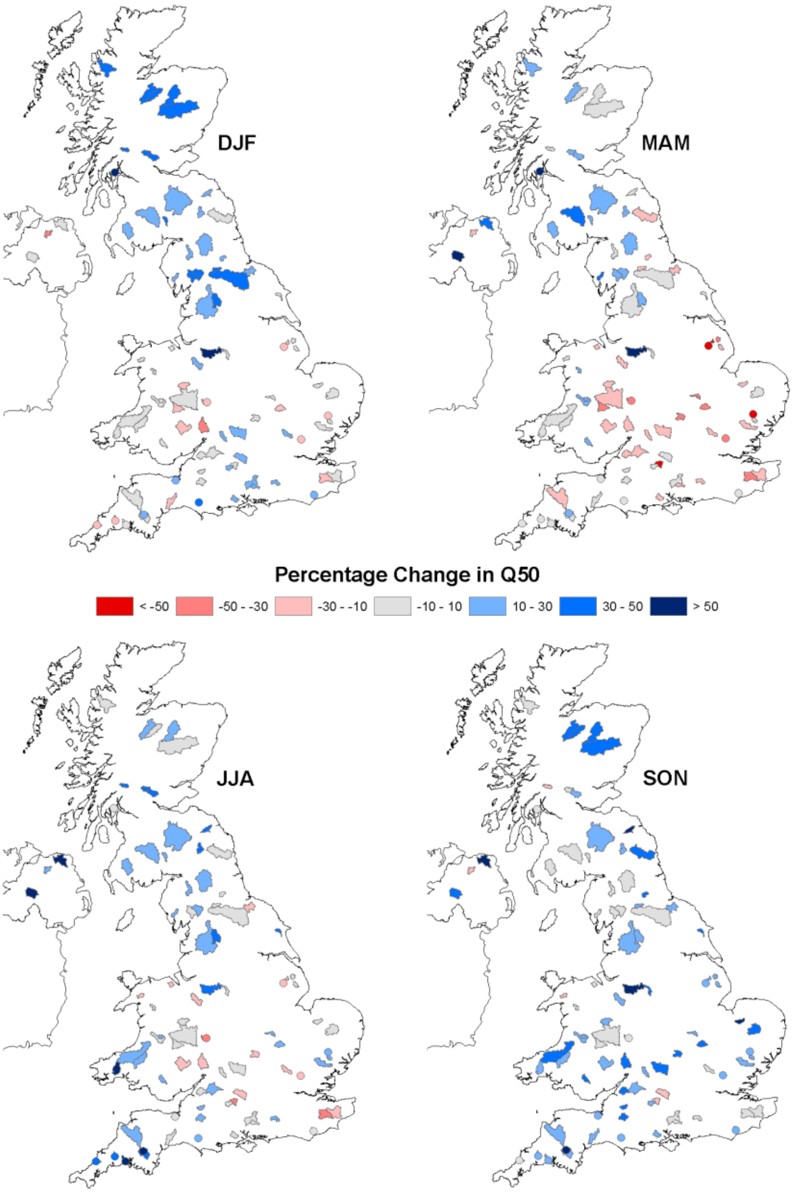


**Figure 3 Seasonal Runoff (median flow, Q50) Trends in the Benchmark Network, 1969 – 2008 (Hannaford and Buys, 2012). Trends expressed as a % of the long term mean in the Q50**

The above studies are limited to the post-1960 period, when a dense network of gauges is available for characterising spatial patterns in trend responses. The paucity of long records has restricted longer-term assessments of runoff patterns. The seasonal trend analysis for Benchmark catchments (Hannaford and Buys, 2012) was complemented with eight 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 see in longer records – there is evidence of a shift, from increasing runoff trends over the 1930s to the 1960s, and decreasing runoff since. A similar pattern of changes in spring runoff was found for the Scottish Dee flow record (1929 – 2004) by Baggalley et al. (2009), who found no significant annual runoff trend, but an increase in spring runoff. The long summer flow records (Hannaford and Buys, 2012) show very mixed patterns and generally rather weak trends.

An even longer perspective is provided by the reconstructed records (Jones et al. 2006; Wilby, 2006), as shown in Figure 4. Wilby (2006) examined trends in moving windows, for every possible start year of the records, for annual, winter and summer mean flows. Whilst 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 very limited evidence for any pronounced changes.

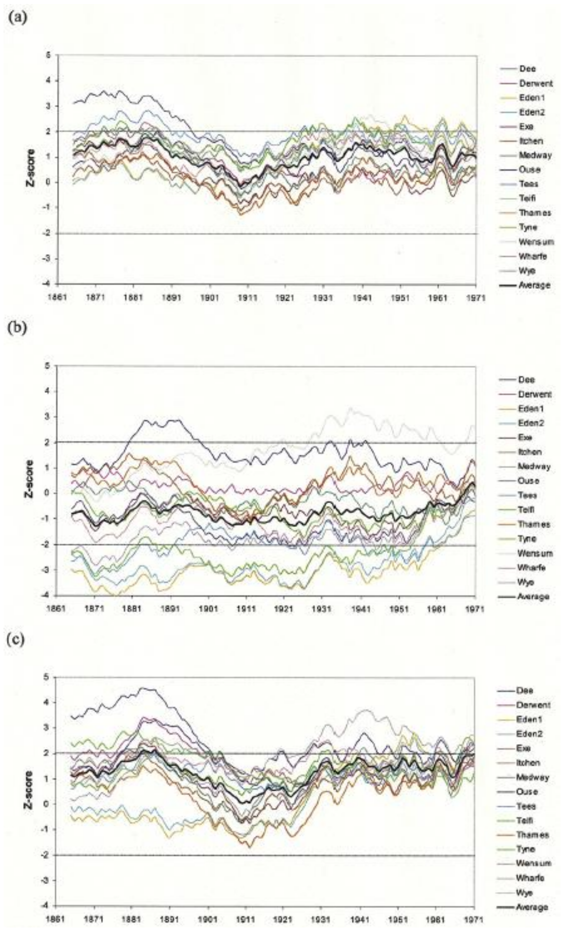


**Figure 4: Results of a moving window trend analysis using the long reconstructed records. Results show Mann-Kendall test for significant trends (Zs) in (a) winter (b) summer and (c) annual mean flows. The dashed horizontal lines show the Zcritical value for the 95% confidence range. Trend statistics lying above (below) the line indicate significant increases (decreases) in flow since the corresponding date. From Wilby (2006)**

### 3.2 High flows and indicators of flooding

As would be expected in a wet country, and given that the floodplain is part of a river's natural province, some form of localised flooding can be expected to occur in most years in the UK. In the recent past, however, flooding has been at the forefront of public attention, and there is a widely held perception that flood risk is increasing. In part, this is due to a succession of major flood events. The most notable widespread flood events of the last 15 years are listed in Table 2. The selection represents the floods which have commanded the greatest public attention, and have been studied in the scientific literature.

**Table 2: Recent major flood events in the UK (reproduced from Hannaford and Hall, see references therein)**

| Date | Areas affected | Hydrology | Impacts |
|---|---|---|---|
| Easter 1998 | English Midlands | Persistent heavy rain falling on near-saturated catchments. 48-h rainfall Return Periods (RP) 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 E and W. 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 World War II. 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-h rainfall record for the UK with an RP of >1800 years. New maximum flows in >20 catchments in NW 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: £200million. 1 fatality. |

A nationwide assessment of trends in river flooding was first carried out as part of research for the Flood Estimation Handbook (FEH). Robson et al. (1998) and Robson (2002) studied peak flow data for the 890 FEH gauging stations – a significant proportion of the UK network. These data were pooled in a national-scale trend analysis which considered magnitude (of Annual Maxima, AM) and frequency (Peaks-Over-Threshold, POTs) for 1941–1980 and 1941–1990 study periods. No significant trends were found for the whole national data set, nor for separate broad-scale regional and seasonal analyses. Instead, these authors found pronounced inter-annual variability and evidence of long-term climatic fluctuations.

One issue with the national-scale approach of Robson and co-workers is the aggregation of a large number of different catchments within the same analysis, including catchments affected by a range of anthropogenic disturbances which may serve to modify any climate-driven flood signals. The

Benchmark Network has since been used to examine evidence for climatic-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. Indicators included 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, particularly in the maritime-influenced upland areas of the north and west. A majority of POT frequency trends were also positive, and flood magnitude increased at 20% of the sites, but, importantly, there were not always increases in peak flow at sites where high flows have become more prolonged (Figure 5). In contrast with the picture for the uplands, few compelling flood or high flow trends were found in the English lowlands: many significant flood magnitude trends were influenced by the 2000 floods towards the end of the series.

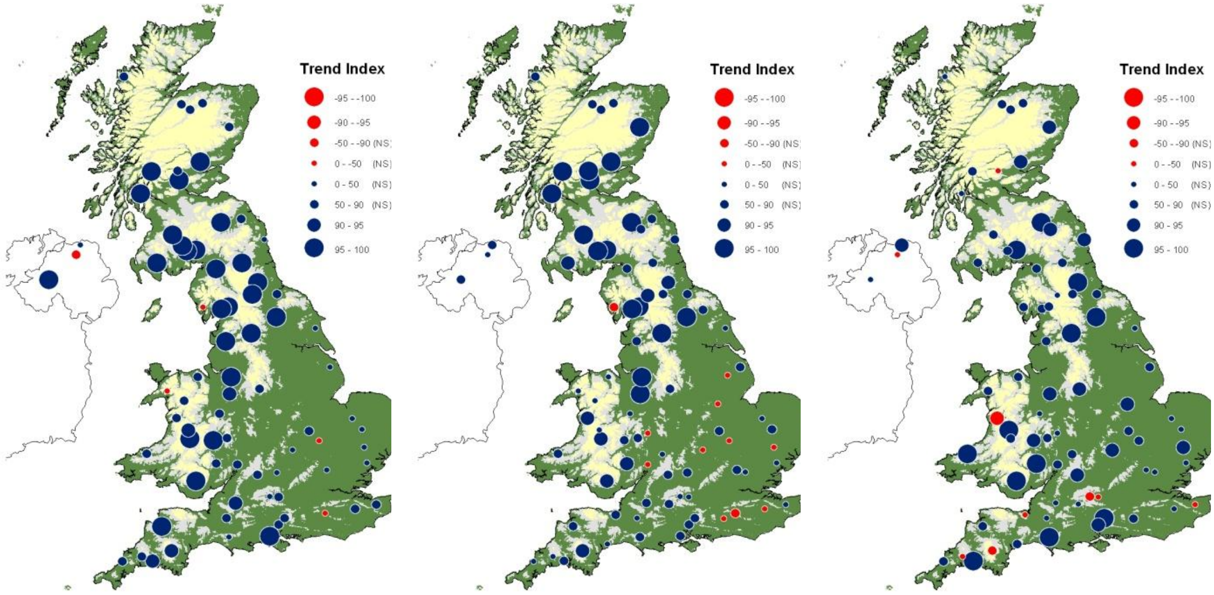


**Figure 5 High flow trends in the UK Benchmark Network. (a) 10-day maximum flow, (b) high flow duration, number of days above Q10 threshold, (c) instantaneous Annual Maximum flow. Legend shows trend index equivalent to p value of statistical significance test (95 = p > 0.05). Dark circles are positive trends, grey circles negative. Adapted from Hannaford and Marsh (2008).**

A recent seasonal analysis (Hannaford and Buys, 2012) added greater detail to this picture: winter high flow (q5) 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 3). This study also found evidence for increasing high flows in some lowland catchments. Trends in spring and summer were more mixed, although some locally important increases in high flows were observed in both seasons. Quinn et al. (2010), also used the Benchmark Network in a national scale assessment, but focused on an index of flashiness rather than flood/high flows *per se*. The study found evidence of increased flashiness in winter in the northwest and parts of southern England and Wales, and increases were also observed in autumn for areas where runoff and high flows have increased (Hannaford and Buys, submitted). In contrast, trends in spring were positive but not regionally coherent, whilst weak decreasing trends in flashiness were observed in summer.

A number of regional studies of flood trends have been carried out over the last two decades, 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. Much of the earlier work focused on Scotland, where several damaging floods in the early 1990s motivated the study of trends in flood records. Black and Burns (2002) found that the late 1980s and early 1990s contained a cluster of the highest floods on record for many catchments in western Scotland. Werritty (2002) reached similar conclusions, finding positive trends over a comparable period, which were also concentrated in western catchments. 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 West 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 in seasonality 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, that were primarily related to circulation-driven changes in rainfall. Decreasing high flows in spring were attributed to declining snow cover. Morris et al. (2012) have recently develop a suite of 10 indicators (including seasonality, frequency and duration) to detect changes in medium and high flows in a network of 56 stations around England and Wales. Only a preliminary analysis was undertaken, finding increases in autumn and winter flows and decreases in summer, and increases in high flow in western localities.

As with annual and seasonal river flows, studies of change in high flows have largely focused on the well-instrumented post-1960 period. National-scale assessments of trends in flooding have provided some long-term context for recent trends, by examining a handful of longer flood records or proxy records such as long-term winter rainfall. Generally, little compelling evidence of long-term trend was found compared to the pronounced background variability (e.g. Robson et al., 1998). Hannaford and Marsh (2008) found that the recent increases in high flows in upland Benchmark catchments are not necessarily seen if analyses are extended to the full period-of-record. The Wye (Wales) and the Dee (Scotland; See also Figure 2) were analysed for trends over their full records (1937 – 2003 and 1929 – 2003 respectively), and trends were found to be much less steep (and often non-significant) in the long records than in the 1969 – 2003 study period used for the national Benchmark trend analysis (Figure 6).

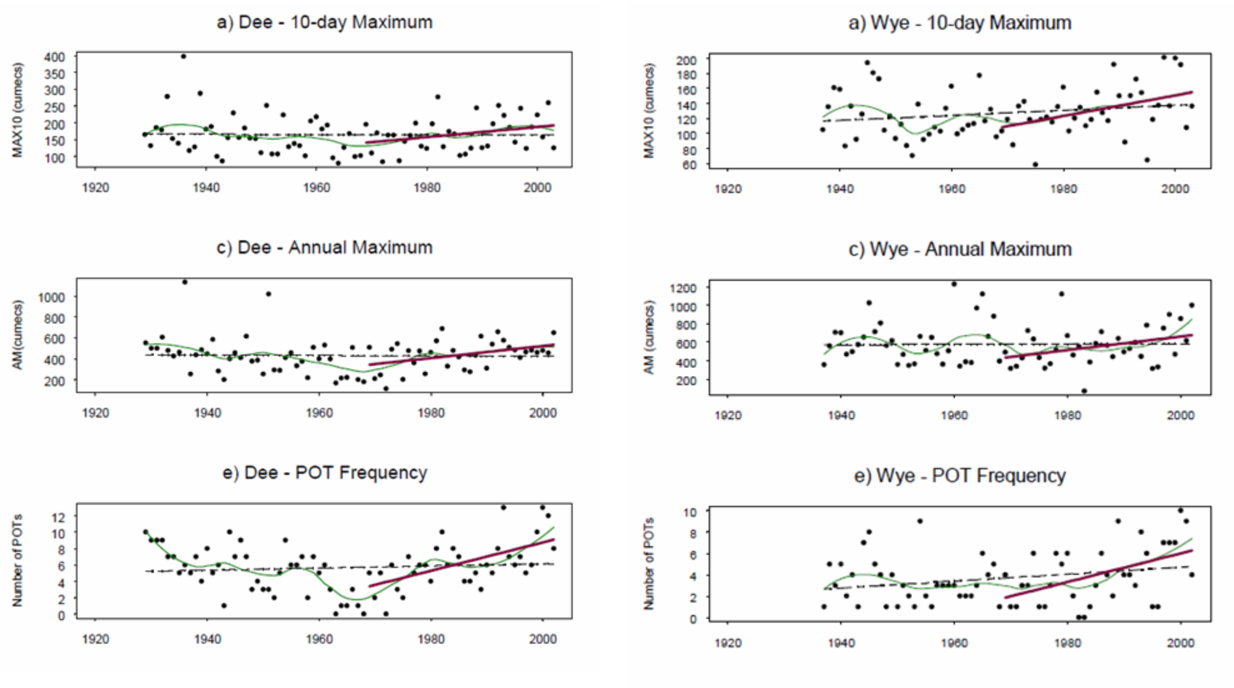


**Figure 6 Time series plots of three high flow indicators for the river Dee (Scotland) and Wye (Wales), comparing trends over the full period-of-record with trends over the 1969 – 2003 period (cf. Figure 5). Adapted from Hannaford and Marsh, 2008**

Long-term trend analyses of flooding are lacking, particularly for very long timescales (i.e. back to the turn of the twentieth century or earlier). A detailed study of one of the longest available UK flood records (1883–present), the Thames at Teddington (Marsh and Harvey, 2012), revealed no long-term change in flood magnitude, despite pronounced increases in temperature, winter rainfall and annual runoff. However, maximum river levels have decreased over the period, reflecting the influence of river engineering and management practices. Overall, this work demonstrates that the Thames displays some resilience to observed climatic changes, and further underlines the findings from multi-catchment analyses that increases in rainfall and high flow duration are not necessarily matched by changes in peak flow magnitude. A long-term record is also available for the River Avon (Marsh and Hannaford, 2007), which confirms a general lack of trend in a partial flood series extending back to 1846. There is an apparent trend towards increasing magnitude if only the instrumented (post-1937) record is considered, but in the long-term context the floods of 1998 and 2007 are of an equivalent magnitude to events in the nineteenth century.

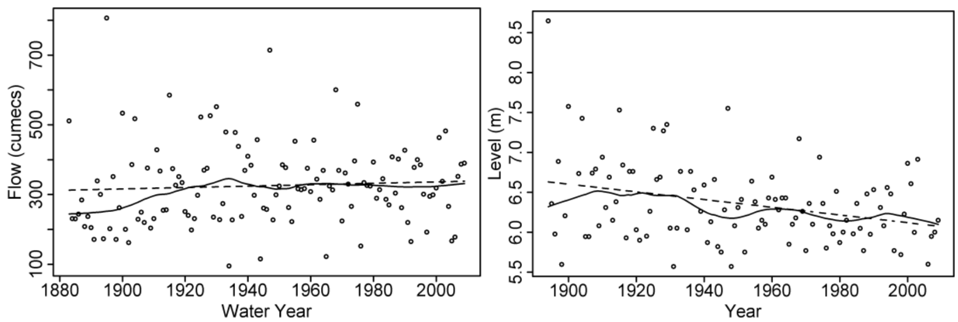


**Figure 7 Long-term trends in flood magnitude at Teddington (Annual Maximum, left) and lock levels (right) for the River Thames. Adapted from Marsh and Harvey (2012).**

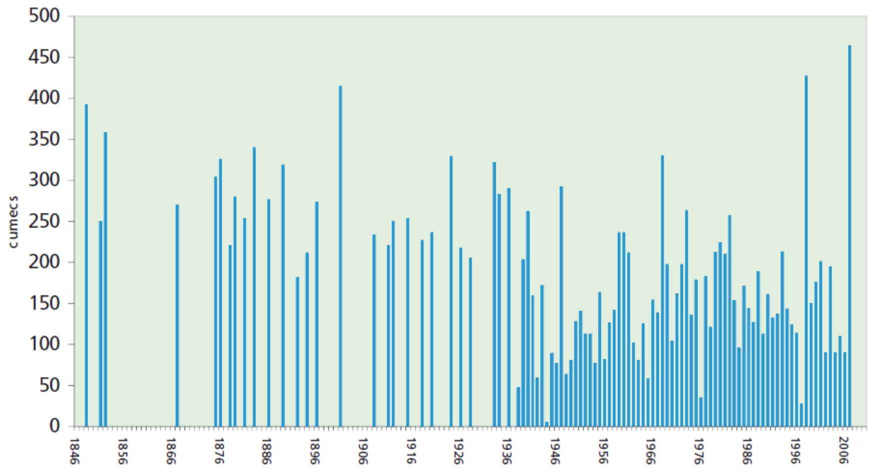


**Figure 8 Long-term time series of flood events on the river Avon at Evesham (Marsh and Hannaford, 2007)**

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 therefore 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. 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 (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. An example is shown for the Eden (Cumbria), based on instrumental, documentary and epigraphic sources (Pattison and Lane, in press).

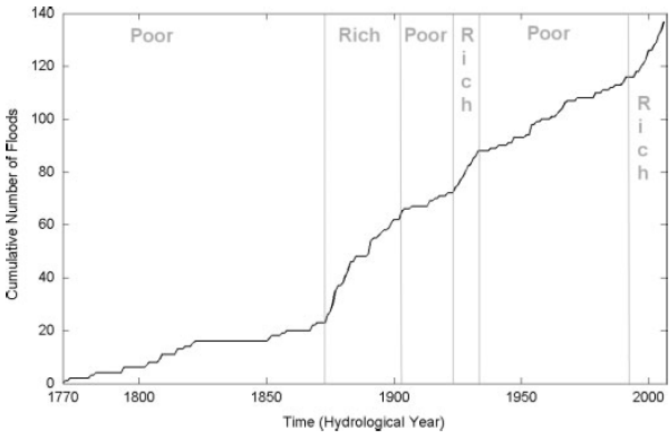


**Figure 9 Cumulative number of floods as a function of time, for a long record of flood occurrence for the river Eden at Carlisle (Pattison and Lane, in press)**

Whilst detectable changes in flood magnitude or frequency have proved rather elusive, it is clear that, despite major expenditure on flood alleviation measures, there has been an increasing vulnerability to the consequences of flooding in the 20th century. This increase in vulnerability has been due to developments in floodplains which are of economic value: many cities and communications links are located in floodplains. Similarly, the economic consequences of flooding have also increased because of the increasing amount of goods in properties and increasing costs of repair. Such increases in exposure undoubtedly contribute to increasing flood risk, and observed trends towards increasing damages associated with flooding, which have been reported across Europe for the latter half of the twentieth century (Barredo, 2007).

### 3.3 Low Flows and hydrological drought indicators

In comparison with the other end of the regime, low flows have received less attention in assessments of hydrological change. Hannaford and Marsh (2006) carried out the first national-scale assessments of trends in low flows, using the Benchmark network, analysing indicators of low flow duration (number of days below Q90) and magnitude (7- and 30- day annual minima). These authors concluded there was little compelling evidence for change over the 1960 – early 2000s. Increasing low flow trends from 1973 – 2002 were found in western catchments (as for annual runoff and high flows), but when analyses were started in the early 1960s, these trends were not significant; trends were sufficiently weak to be modified by a dry period at the start of the series. No significant trends were found across the English lowlands – although a tendency for weak decreasing trends was noted. A similar result was reported for the study of Wade et al. (2005), which examined Q95 trends in 47 river flow records over the 1970 – 2002 period, and found very few significant trends.

Recent studies have found a similar lack of evidence for low flow trends. Marsh and Dixon (2012) and Marsh et al. (in preparation) analysed Q95 trends for the national runoff 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 low 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. However, 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 no coherent 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 some UK benchmark catchments over the 1962 – 2004 period. This serves to illustrate the importance of study period, as this study ended with the 2003 drought (and emerging drought in 2004) whereas Hannaford and Buys (submitted) ends after the wet summers of 2007 and 2008. Such sensitivity to short wet or dry periods underlines that these trends are generally weak – overall, there seems to be little evidence of any strong decrease in low flows since the 1960s. Regional studies have also found little evidence for low flow changes (Werrity, 2002; Dixon et al. 2006) in Scotland and Wales, over broadly similar timescales.

As with other regime indicators, there have been few studies of long-term (whole 20$^{th}$ century) changes in low flows. The issues which hinder the use of long records in general are even more problematic for low flows, as abstractions, discharges and regulation can substantially modify low flow regimes. Most long records in the UK are in the lower reaches of large catchments, and associated with urban areas, so artificial influences render them unsuitable. One instructive example is the long Thames record, for which the 30-day minimum flow time series is illustrated in Figure 10 (Hannaford and Marsh, 2006), contrasting gauged and naturalised flows. The decreasing trend in the gauged flows is a result of a seven-fold increase in abstractions to support much of London's water needs. The naturalised trend shows a modest increase, but this is undoubtedly influenced by influenced by under-estimation of low flows during the first half of the record; however, there is a positive trend over post-1951 period when the low flow series is substantially more homogenous. The reversal of a long-term trend by human activities underlines the need for caution in interpreting long low flow records.

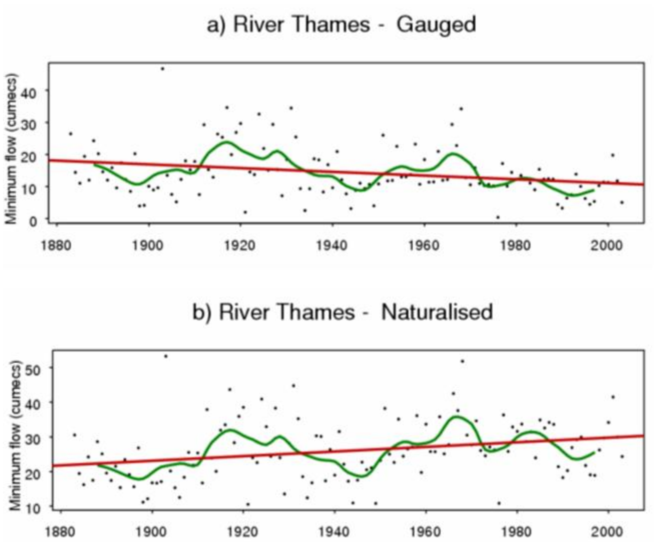


**Figure 10 Comparison between the Thames at Teddington/Kingston 30-day minimum series based on gauged and naturalised records. The red line shows the long-term trend, the green line shows a LOESS smoothing curve. Adapted from Hannaford and Marsh, 2006.**

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. the 2003 drought and 2004 – 6 drought (Marsh et al. 2007), and a drought throughout 2010 – early 2012 (Kendon et al. 2013). The 1990s also saw notable droughts (in 1988 – 1992 and 1995 – 1997). Beyond the low flow 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 characterised by low river flow time series: the annual and seasonal trends highlighted above are all relevant for drought assessment, as are other indicators (groundwater levels, meteorological datasets). There have been a number of studies which address changes in meteorological drought indicators (e.g. Burke et al. 2010), which are not considered in detail here. 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 (Lloyd-Hughes et al. 2012) show regional-scale hydrological and meteorological droughts for five UK regions (North West, North East, South West, and South East, with the latter being sub-divided 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 (the 1990s, late 1970s), as shown by the example in Figure 11. Interestingly, the meteorological catalogue shows many significant droughts through the twentieth century, which are of similar (or greater) duration and intensity as those of the recent past. Evidence from the 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. 1921/22; 1933/34), but also including a number of severe droughts in the late 19$^{th}$ 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 nineteenth 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 the rest of the 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 – 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. Clusters of successive dry winters were identified as a major driver of hydrological drought in the English lowlands, which relies on winter rainfall to replenish groundwater reserves – the prevalence of major droughts in the nineteenth century is largely a result of drier winters during this time. The causes of this variability, however, remains poorly understood (see Section 3.5).

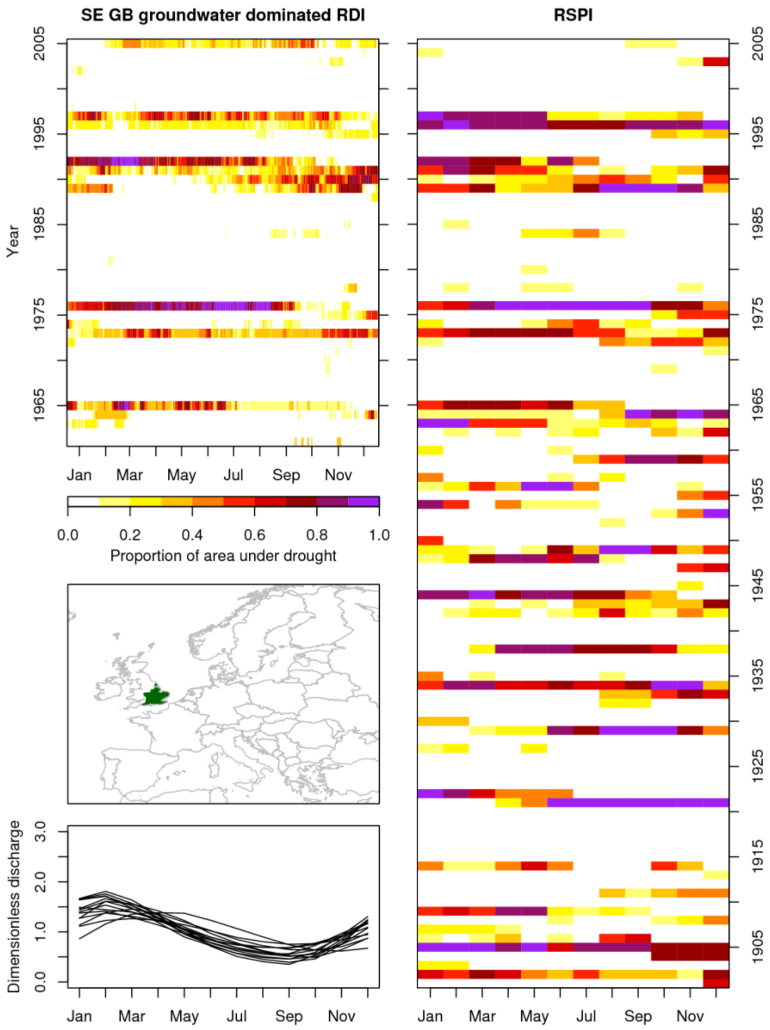


**Figure 11 Example Drought Catalogue Page for South East England (groundwater dominated catchments). The RDI (Regional Deficiency Index) shows Regional river flow droughts, whilst the RSPI (regional Standardized Precipitation Index) shows meteorological droughts. After Lloyd-Hughes et al. 2012 and Hannaford et al. (2011).**

**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. |
| 1887–1888 | Late winter 1887–summer 1888 | Major drought. High ranking rainfall deficiencies across a range of timeframes. Very widespread (across most of British Isles). Extremely dry five-month sequence in 1887. Primarily a surface water drought – severe in western Britain (including the North-West). |
| 1890–1910 | 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. |
| 1921–1922 | Autumn 1920–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 East Anglia and the South-East; parts of Kent reported <50% rainfall for the year, 1921); episodic in north-west England. |
| 1933–1934 | Autumn 1932–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–Nov | Major drought. Intense three-season drought – most severe in eastern, central and north- eastern England. Significant spatial variation in intensity. Modest groundwater impact. |
| 1976 | May 1975 – Aug 1976 | Major drought. Lowest 16-month rainfall in England and Wales 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. |
| 1990–1992 | Spring 1990–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. |
| 1995–1997 | Spring 1995–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 the hot summer of 1995). Initial surface water stress, then very depressed groundwater levels and much diminished lowland stream network. |

### 3.4 European Perspective

There have been a multitude of trend assessments for European countries over the last ten years, including a growing trend for national studies using Reference Hydrometric Networks (or RHN-like catchments), e.g. in France (Renard et al. 2008), the Nordic countries (Wilson et al. 2010) and many others. As for the UK, a common feature of much of the European literature is a lack of strong evidence of change, and a recognition of the underlying role of multi-decadal variability in driving observed trends; strong variability in flood frequency appears to be a feature over decadal to century timescales since the 1400s (Brázdil et al. 2006).

Pan-European assessments of change were relatively rare until very recently, with the notable exception of Hisdal et al. (2001), who conducted a European wide assessment of hydrological drought, using the FRIEND-EWA (Flow Regimes in Experimental Networks and Data European Water Archive), and found it was not possible to assume droughts had become more severe or frequent.

This gap has been filled in recent years by several assessments of change at the continental scale, based on a European wide network of near-natural catchments assembled under the auspices of FRIEND and the EU-WATCH (Water and Global Change) project. Stahl et al. (2010) collated data for over 400 catchments from 11 European countries from across Europe – although with a bias towards northern and western Europe, with limited coverage in the Mediterranean. Data for 36 UK benchmark catchments were used in the analysis. The results suggest that increasing winter and annual runoff trends in parts of the UK since the 1960s are part of a wider pattern of increased runoff in Northern Europe, in contrast with decreasing annual runoff in southern Europe (Figure 12). The study also examined monthly flow trends, and generally found similar results for winter months to UK studies. However, Stahl et al (2010) found stronger evidence of decreased summer river flows in the UK, as well as decreasing trends in low flows (see Section 3.3). For the spring and summer months, negative streamflow trends were found over a large part of Europe. A follow-up study (Stahl et al. 2012) shows that high flow (7-day maximum) increases in the UK were also part of a wider pattern of increasing high flow in northern Europe.

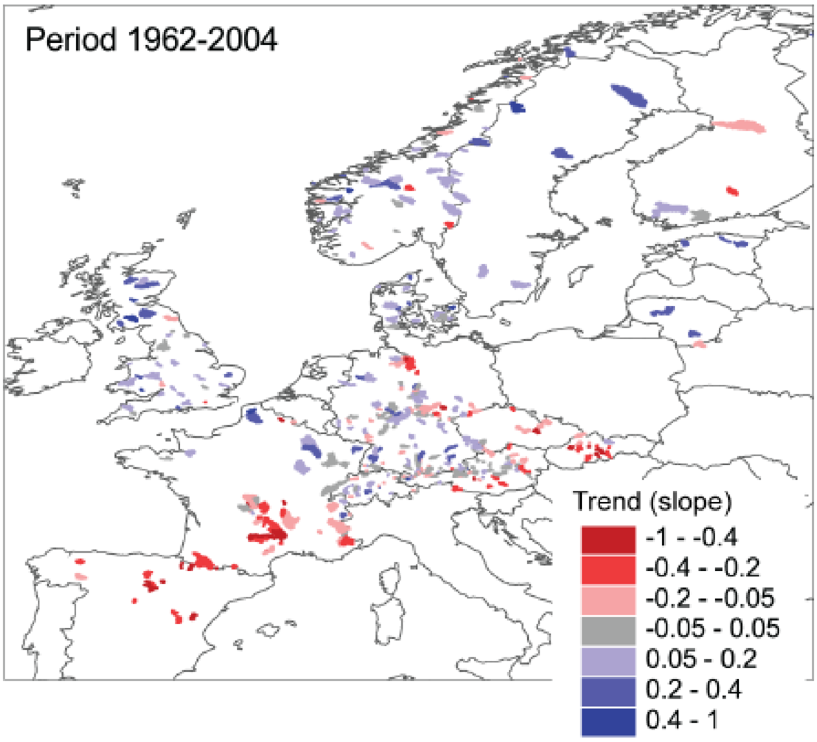


**Figure 12 European Runoff Trends (after Stahl et al. 2010).**

### 3.5 Attribution of observed trends

Merz et al. (2012) argue that flood 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 currently 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 weak, largely as a result of the methodological issues outlined in Section 2. However, the use of Benchmark catchments is at least an attempt to capture a proof of inconsistency (i.e. that trends are not consistent with anthropogenic disturbances, which have been controlled in the specification of the network). Hence, most of the reported patterns of change are likely to be climate-driven. However, whether they are driven by anthropogenic forcing, or natural variability, is a more vexed question, addressed later in this section. Firstly, an assessment is made of broad consistency with other climate changes. Detailed assessments of climate changes are given elsewhere, so only a very brief summary follows.

#### 3.5.1 Consistency with observed climatic changes

The patterns of annual and seasonal flows since the 1960s generally agree with published studies of observed rainfall over a similar timeframe (although note that the exact study periods vary). Spatial patterns of runoff can be compared with the UKCP09 assessment of observed rainfall from 1961 – 2006 (Jenkins et al. 2008). For both rainfall and flow, the strongest increases in winter are found in the uplands in the north and west. The patterns for spring are also broadly consistent, although decreases in lowland (southeast) Britain are more pronounced for flow than for average rainfall (with most of this area actually showing no trend for rainfall). Conversely, for summer the rainfall trends are more markedly negative, across much wider areas (including north Wales and northwest England), whereas for summer flows there is limited evidence for decreasing trends: trends were generally weak and sensitive to study period. In autumn, the association is strongest: the largest rainfall increases are seen in a belt from southwest England through central areas to the east coast, and in northeast Scotland, which corresponds well with the zones which have the steepest runoff and high flow trends (Hannaford and Buys, 2012). Observed increases in high flows also correspond well with observed increases in heavy rainfall, which are generally greatest in winter, and in upland areas (e.g. Maraun et al. 2008; Burt and Ferranti, 2011).

There are some parallels between rainfall and flow patterns, but also important differences, which are likely to be influenced by other climatic changes. The greater agreement between winter and autumn patterns compared to spring and summer may partly reflect the role of changing evapotranspiration patterns. An increase in average temperatures in spring across much of England (Jenkins et al., 2008) is likely to have increased evapotranspiration, which may explain reduced spring flows. However, following a similar argument, there is very limited evidence for any strong decrease in summer flows despite significant warming (Jenkins et al., 2008). The role of groundwater storage (which may result in carry-over between seasons) may also play a significant role in explaining the complex patterns seen in the English lowlands, and the lack of agreement between spring/summer trends and rainfall. Furthermore, the different study periods must also be considered, with the rainfall analysis starting in the 1960s and ending in 2006 (after the 2003 and 2004 – 6 droughts), whereas seasonal benchmark trends were analysed to 2008 (following two very wet summers).

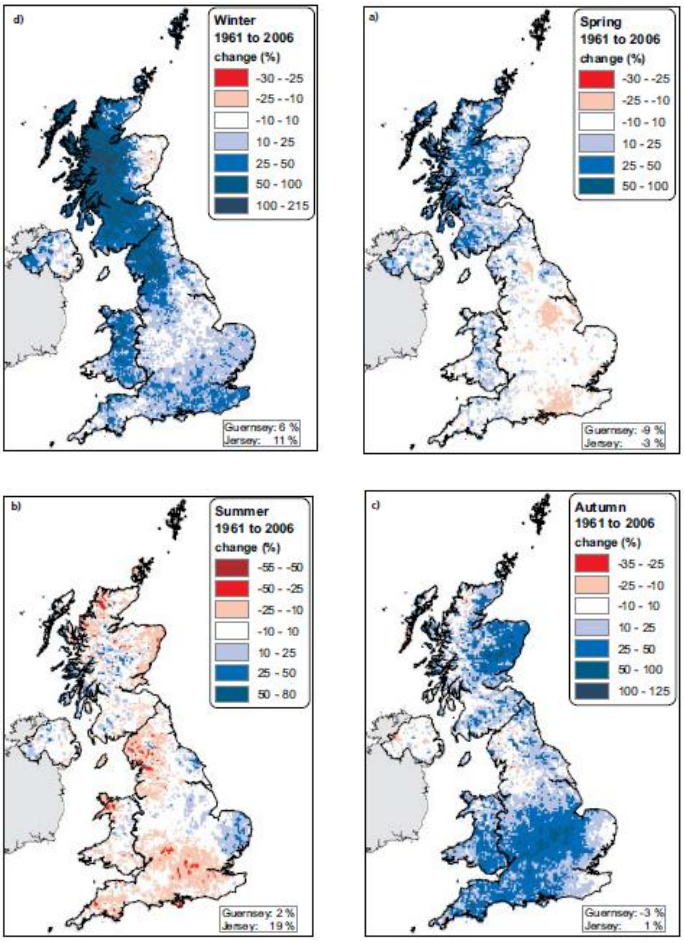


**Figure 13 Regional patterns of precipitation change, 1961 – 2006 (Jenkins et al. 2008).**

Other temperature-driven changes may also be influencing river flows. There have been very few observational studies of changes in snowfall, but Barnett et al. (2006) report decreases in winter snow cover in Scotland between 1961 and 2004. Whilst melt rates may increase in a warming world, it is likely that snowmelt and frozen ground have become less influential in the UK. Snowmelt, runoff on frozen ground and ice-jams were a major contributory factor in many large historical floods, but have likely declined in importance as runoff and flood generating mechanisms. Baggalley et al. (2009) attribute an overall increase in spring flows for the Scottish Dee (1929 – 2004) to a decrease in the contribution of precipitation falling as snow (relative to an increase in rainfall) in the Cairngorm mountains. It is perhaps less likely that snowmelt patterns are the cause of similar changes in spring in the long records used by Hannaford and Buys (2012), largely from the English lowlands, but changes in snowmelt relevant for river flow are undoubtedly important and have received relatively little attention. For the Tay (Scotland), McEwen (2006) reveal that snowmelt played a greater flood generation role in the nineteenth century relative to the twentieth. MacDonald (2010) showed that in a >300 year record for the Ouse (Yorkshire, northern England), the relative role of snowmelt and rainfall has remained broadly similar. Understanding the relative roles of snow and rainfall as flow generation mechanisms should be a major area for future work.

### 3.5.2 Attribution to climate change or climate variability?

There is unequivocal evidence that the latter part of the twentieth century, the period over which the evidence for river flow change have been assessed, has seen unprecedented warming (IPCC, 2007) on a global scale and that it is likely that this is attributable to anthropogenic greenhouse gas emissions. More locally, the UK has seen significant warming in the recent past: Murphy et al. (2009) report that the Central England Temperature (CET) series increased by about 1°C between 1980 and 2006, and there is growing evidence that this warming is likely to be due to human activities. Clearly, the changes in river flows reported here have all occurred against a backdrop of increased temperatures most likely attributable to human activity. This may be expected to result in changes to river flows, but the complex chain of causality from temperature to river flow (as compared with, say, temperature to sea-level rise) hinders attribution of observed trends in river flow patterns. Increases in temperature could increase precipitation locally, but evapotranspiration, soil moisture fluxes and snowmelt will also be influenced by temperature. There are also many other factors which complicate the assessment of attribution, considered in the following assessment of consistency between observed trends and expected changes under global warming.

There are some parallels between observed trends 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, so a great deal of research has sought to explain observed hydrological change in this context. The North Atlantic Oscillation has commanded the greatest scientific attention. The NAO (with the NAO Index expressed as the difference in sea-level pressure between the subtropical North Atlantic high and the Icelandic low) has been shown to influence the preferred storm track over the North Atlantic into Europe, particularly during the winter (generally December–March) period. In positive NAOI years, enhanced westerly airflows and a more northerly storm track results in increased winter precipitation over northern Europe and Scandinavia, causing increased precipitation in northern and western areas of the UK. Recent studies of runoff and high flows have found strong relationships between the NAO and winter and annual runoff (e.g. Laize et al. 2010). Hannaford and Marsh (2008) correlated the NAOI with high flows, and found strong correlations with some indicators, particularly duration of high flows. Relationships between the NAO and flow extremes in upland areas were reported by Biggs and Atkinson (2011), but were found to be less prevalent by MacDonald et al. (2010). Other authors have examined synoptic-scale Weather Types, rather than large-scale indices like the NAO, but have generally reached similar conclusions regarding the importance of westerly airflows in controlling river flow and floods (Pattison and Lane, in press) whilst their absence during anticylonic conditions plays a major role in droughts (Fleig et al. 2011).

Whilst the NAOI can be linked to some river flow indicators, the chain of causality between atmospheric circulation patterns and streamflow is complicated, particularly for flow extremes (Kingston et al., 2006), and a range of circulation patterns other than the NAO may be influential across varying spatial and temporal scales. Furthermore, whilst the NAO is clearly a dominant driver of winter rainfall, relationships with rainfall are stronger than for flow as basin properties play a large part in modulating the climate signal (Laize and Hannah, 2010). Notwithstanding these limitations in our current understanding of exactly how the NAO influences river flows, this body of research suggests the wetter winters observed in upland areas are influenced by changes in westerly airflows linked to multi-decadal variability in the NAO, and the increasingly positive NAO in the latter part of the 20th century is therefore likely to be a strong factor in causing the observed increases in runoff and high flows. 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. Gillet et al., 2002; Dong et al. 2011). Furthermore, recent years have seen some very dry winters, associated with strongly negative NAO conditions, reflecting a downturn in the NAOI since the mid-1990s.

It is also important to acknowledge that the NAO is not the sole large-scale atmospheric influence on the UK hydro-climate, and other work has sought to examine flood and drought events in the context of other climate drivers. For example, the Scandinavia Pattern has been linked to autumn/winter flooding (Pall et al. 2011, Lavers et al. 2012) in the UK. In addition, there are numerous interlinked drivers of north Atlantic climate variability which may influence the manifestation of teleconnections such as the NAO. The Atlantic Multidecadal Oscillation (AMO) integrates sea-surface temperature variability over much longer timescales, and its recent warm phase has been linked to wetter summers and drier springs in the UK (Sutton and Dong, 2012). Recent extremely wet summers (e.g. 2007 and 2012) have been associated with persistent anomalies in the location of the Jet Stream; these patterns could be linked to variations in North Atlantic sea-surface temperatures associated with the AMO, but other authors have noted possible links between changes in the Jet Stream and changing thermal gradients associated with decreasing in Arctic sea ice as a result of anthropogenic warming (e.g. Francis and Vavrus, 2012).

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 in the English Lowlands. In the Benchmark studies, summer flow trends exhibit very mixed patterns, but generally positive trends outweigh negative trends. Where declining low flow or summer flow trends are found, they are sensitive to study period and directionality and magnitude of change can be altered by clusters of high or low flows: evidence from long records also shows limited evidence for change. In the absence of solid evidence, it is therefore rather premature to attempt to attribute observed changes to anthropogenic forcing or any other cause. However, the lack of trends in itself is an important result given favoured climate change projections. The UKCP09 scenarios project decreasing summer rainfall (Murphy et al., 2009) for much of the UK, whilst catchment modelling studies suggest this will lead to pronounced decreases in summer river flows (Prudhomme et al. 2012; Christierson et al., 2012), whilst low flows are expected to decrease, particularly in southern England (e.g. Arnell, 2011). On the basis of the review of evidence presented herein, there is no regionally coherent decrease in summer flows or low flows that could be taken as strong evidence for such climatic changes already becoming manifest, seemingly at odds with studies projecting decreased flows by the '2020s' (a 30-year period covering 2011 – 2040) relative to a 1961 – 1990 baseline (von Christierson et al. 2012).

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, whilst observational studies are subject to a range of limitations in the data and methodologies used, described in Section 2. In particular, the low signal-noise ratios seen in hydroclimatic time series may mean changes are not detectable for many decades in the UK (Wilby, 2006). As such, the short records and high variability 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. Moreover, the generalised finding of "no trend" in summer flows/low flows masks significant regional differences: perhaps one of the most prominent features of Benchmark trend assessments for the English lowlands (e.g. Figure 3) is the spatial heterogeneity of trend responses. In some catchments, evidence for change may be much stronger, and understanding the causes of this heterogeneity (whether due to variation in catchment properties, especially variations in groundwater storage, or other anthropogenic drivers such as land use change) is a focus for future work (see Section 5). Notwithstanding these caveats, the lack of coherent change in summer is somewhat different from that expected under climate change, and a much more confused picture emerges. In contrast, summer decreases are one of the more robust results from the latest probabilistic modelling studies (Prudhomme et al., 2012; Christierson et al. 2012), albeit with a wide range in magnitude of projected changes.

It is clear from this summary that there is currently no strong evidence for anthropogenic warming influences on river flows – but that this lack of evidence is not enough to rule out an effect being present, due to the challenges to attribution which have been highlighted herein. Arguably, there are few obvious ways this can be overcome in the near future: Wilby et al. (2008) call for more sensitive indicators which allow signals to emerge more readily from noise, whilst the attribution framework of Merz et al. (2012) provides a recipe for greater scientific rigour, but such advances, while improving statistical detection, do little to improve the prospects for robust attribution of anthropogenic global warming signals. In theory, a more robust approach is to use formal detection and attribution methods relying on optimal fingerprinting and related methods. Such methods have been widely applied for climate variables (e.g. the review of Stott et al. 2010) but have only recently been applied to hydrological data. Thus far, attribution has focused on individual events: 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, with groundwater playing a significant role (Kay et al. 2011). Interestingly, this work suggests decreased snowmelt over time has played a role in reducing flood risk.

## 4. Assessment of confidence in scientific understanding

In line with the specification for this review, this section provides and assessment considers the confidence in the evidence for the observed changes, but does not attempt to address whether these changes are due to anthropogenic warming, due the complexities discussed in the previous section.

The assessment is based on the IPCC framework for assessing confidence in scientific understanding. http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf. The assessment is based on the matrix shown in the top right hand corner of Figure 14. Judgment of the respective class is clearly subjective – the “evidence” categorisation has drawn on the amount and quality of evidence, strength/significance of reported trends and whether they are regionally coherent. The “Agreement” categorisation has considered whether published studies agree, but also whether there are differences between different study periods (including in the same studies), or when trends in longer records agree/disagree with those of shorter records.

Clearly, there is a great deal of regional diversity in observed trends. For ease of interpretation, two separate “regions” are considered: lowland south-east England, and upland north-west Britain. Clearly. these are a simplification, and just intended to provide an overall contrast between the two areas rather than to truly represent the range of individual catchments within each.

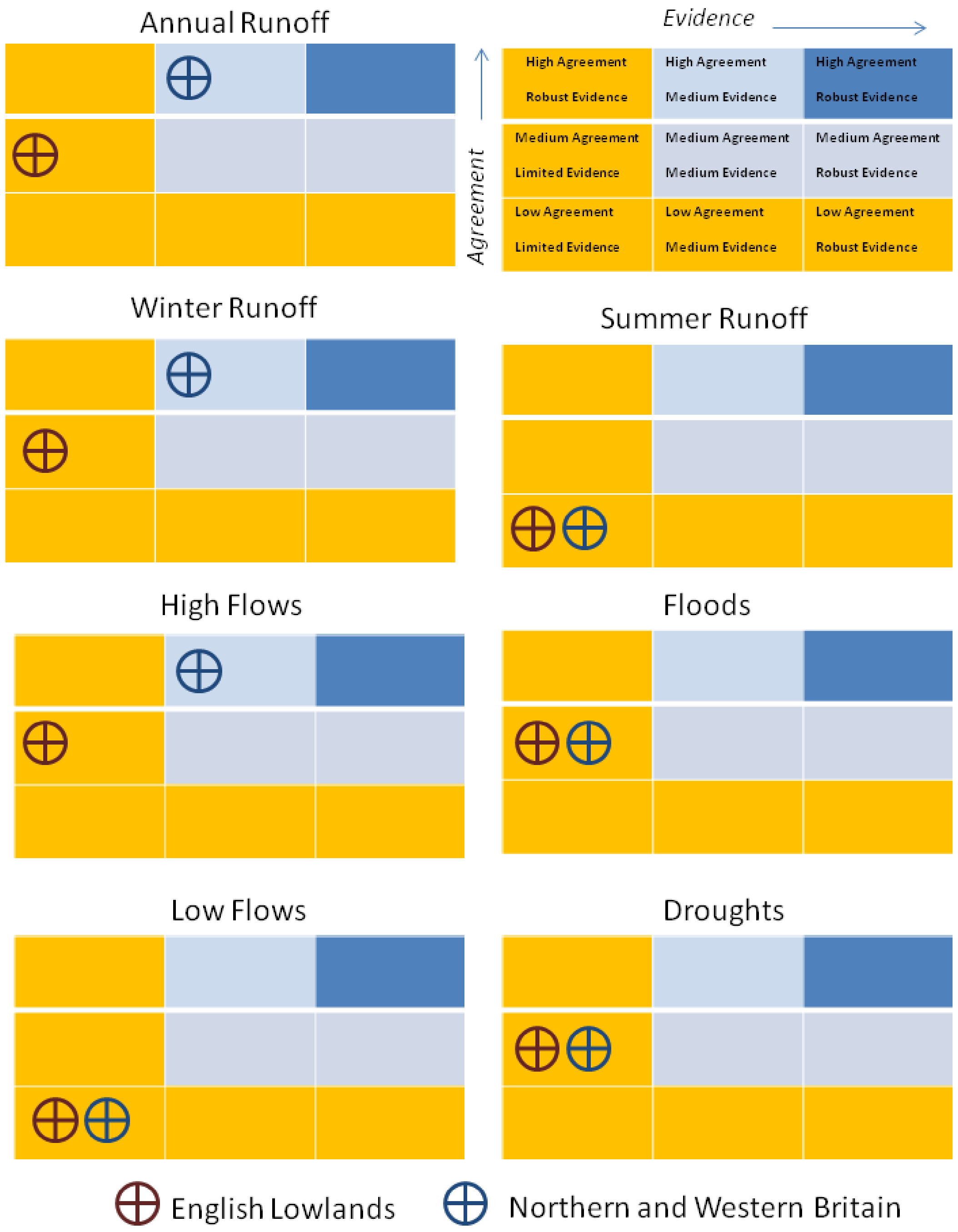


**Figure 14 Confidence Assessments using IPCC framework for scientific understanding, for seven key indicators**

## 5. Knowledge Gaps

The following knowledge gaps have been identified as areas for further research. The list is not intended to be comprehensive, but to highlights obvious areas which follow from the issues arising in this review

- Most attempts to link flow trends with meteorological causes have been rather qualitative; parallel analyses of flow with meteorological indicators have generally been carried out for individual catchments or regions (e.g. Bagalley et al. 2009; Biggs and Atkinson, 2011) rather than at a national scale, and largely focused on rainfall datasets. There is a need for in-depth studies which examine trends in river flow alongside complementary climate datasets in synchrony – to determine the relative role of historical changes in precipitation and evapotranspiration in driving observed flow trends, as well as in considering the role of changes in snowmelt storage. There is a paucity of data on snow cover and snowmelt, so this remains a key area for improvement in historical datasets.
- One of the key features of catchment-based analyses is the spatial heterogeneity of trend responses, in the English Lowlands especially: the benchmark catchments show a wide range of trend magnitudes, and sometimes opposing direction, in nearby catchments (see Figure 3). There is a need to examine this heterogeneity and determine whether it is related to catchment properties, e.g. groundwater storage which can influence the response to climate drivers (Laize et al. 2010). Mapping climate changes onto runoff responses is currently confounded by this heterogeneity, so its characterisation is a necessary step before observed changes in flow indicators can be attributed to climatic change or variability. This is a key area of work as future modelling studies suggest sensitivity to climate change is heavily influenced by catchment and aquifer characteristics (e.g. Prudhomme et al. 2010; Jackson et al. 2011).
- The seasonal differences elucidated in this review provide only a limited view of sub-annual changes in streamflow. Monthly flows have not been analysed (with the exception of Stahl et al. 2010, who found seasonal averages can obscure differences between months). There would also be a benefit in examining patterns of changing seasonality, particularly in high and low flow indicators – for example, examining the timing and seasonality of high flows as a potential indicator of climate change (as carried out for Wales by MacDonald et al. 2010). This may help reveal the differences seen in trends in high flows and true indicators of extremes like peak flood discharges.
- Wilby (2006) recommends the development of indicators which may be sensitive to change, to enable the signal of climate change to be more readily detected against the noise of background variability. Numerous authors have suggested the need to examine a range of different indicators (of magnitude, seasonality, duration, etc: e.g. Morris et al. 2012) but such appraisals have been limited thus far. There would be benefit in defining a set of climate change indicators and applying them routinely to a particular set of catchments (such as the Benchmark network or a sub-network within).
- Wilby (2006) also recommends exploiting spatial correlation of flow records to enhance detectability. This has potential for application in the catchment-based analyses, but has not been carried out systematically for across the UK. There are a wide range of methods for examining spatio-temporal trends (e.g. conventional field significance; geostatistical trend detection; see Burn et al. 2012) which have been applied in the USA and Canada, which are yet to be applied in the UK.

- Other direct anthropogenic influences can influence streamflow. While this is controlled insofar as possible in Benchmark catchments, human disturbances cannot be ruled out. The Benchmark selections are provisional, and it is still possible that some of the observed heterogeneity in the English lowlands may reflect patterns of water utilisation which are not known. Moreover, land use and land management change may influence river flows. Whilst previous reviews have generally found limited evidence for land use impacts on flooding catchments > 10km$^2$ (O' Connell et al. 2007), there remains need to examine the extent to which observed trends could reflect changing land-use and land-cover patterns.
- Further analysis of long records is needed to examine recent trends in a longer historical context. Many of the issues associated with interpretation of published studies are due to different record lengths. Multi-temporal trend analysis (such as the moving window approaches used in Wilby, 2006,, Hannaford and Buys, 2012) provide one way of dispensing with fixed study periods. However, in general there is a greater need to move away from standard, linear non-parametric tests in fixed periods, and embrace methods which allow the form of trends to be characterised (see discussions of Clarke (2010) and Hirsch (2011)), as well as tests which quantify changes in statistical properties other than the mean (e.g. changes in variance or persistence). There is also 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 (e.g. Jones et al. 2006), historical proxy data (Brázdil et al. 2006) and other techniques.
- Long records generally show evidence of pronounced variability which influences trend tests, on a range of timescales (inter-annual to multi-decadal). Whilst numerous studies point to such variations, and cite climate variability as a likely cause, there is currently a very limited understanding of the causes of interdecadal variability, beyond a rather general appreciation of the role of the NAO, which is typically quantified rather weakly. There is a need to develop an improved understanding of the climatic drivers which influence historical multi-decadal variability, focusing on a wider range of teleconnection patterns and drivers of interdecadal variability (e.g. the Scandinavia pattern, East Atlantic/West Russia pattern, the AMO, ENSO). Recent work has also pointed to the role of atmospheric rivers (narrow bands of moisture along which moisture is transferred from the subtropics to the mid-latitudes) in major winter flood events in western parts of the UK (Lavers et al. 2011, 2012). There are also numerous studies in the meteorological literature which consider the role of sea ice dynamics (Liu et al. 2012; Francis and Vavrus, 2012), solar activity (Lockwood et al. 2010, Inseson et al. 2011) and a host of other factors in driving northern hemisphere climate variability – the role of such factors in influencing river flow variability is poorly understood at present, but they may be critical to understanding (and potentially predicting) major flood and drought events and their future evolution in a changing climate.

**REFERENCES**


Arnell, N.W., 2011. Uncertainty in the relationship between climate forcing and hydrological response in UK catchments. Hydrology and Earth System Sciences,15(3), 897-912.

Baggaley, N.J., Langan, S.J., Futter, M.N., Potts, J.M., Dunn, S.M., 2009. Long-term trends in hydro-climatology of a major Scottish mountain river. The Science of the total environment, 407(16): 4633-41.

Barnett, C., Hossell, J., Perry, M., Procter, C. & Hughes, G. (2006) Patterns of climate change across Scotland: Technical Report. SNIFFER Project CC03. Scotland and Northern Ireland Forum for Environmental Research, 102pp.

Barredo, J.I., 2006. Major flood disasters in Europe: 1950–2005. Natural Hazards, 42(1): 125-148.

Bayliss, A., Norris, J., Marsh, T.J. 2004. The Wendover Springs record: an insight into the past and a benchmark for the future. Weather, 59, 267 – 271.

Biggs, E. M. & Atkinson, P. M. (2011) A characterisation of climate variability and trends in hydrological extremes in the Severn uplands. International Journal of Climatology. 31, 1634–1652

Black, A.R., Burns, J.C., 2002. Re-assessing the flood risk in Scotland. Science of the Total Environment, 294(1-3): 169-184.

Bradford, R.B., Marsh, T.J., 2003. Defining a network of benchmark catchments for the UK. Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering, 156(2): 109-116.

Brázdil R, Kundzewicz ZW, Benito G. 2006. Historical hydrology for studying flood risk in Europe. Hydrological Sciences Journal 51: 739–764.

Burke, E.J., Brown, S.J., 2010. Regional drought over the UK and changes in the future. Journal of Hydrology, 394(3-4): 471-485.

Burn, D.H., Hannaford, J., Hodgkins, G.A., Whitfield, P., Thorne, R. and Marsh,T.J. 2012. Hydrologic Reference Networks II. Using Reference Hydrologic Networks to assess climate driven change. Hydrological Sciences Journal, 57, 1580-1593.

Burt, T. P. & Ferranti, E. J. S. (2012) Changing patterns of heavy rainfall in upland areas: a case study from northern England. Int. J. Climatol. 32, 518 – 532.

Chen, Z., Grasby, S.E., 2009. Impact of decadal and century-scale oscillations on hydroclimate trend analyses. Journal of Hydrology, 365(1-2): 122-133.

Christierson, B.V., Vidal, J.P., Wade, S.D., 2012. Using UKCP09 probabilistic climateinformation for UK water resource planning. Journal of Hydrology 424-425, 48-67.

Clarke, R.T., 2010. On the (mis)use of statistical methods in hydro-climatological research. Hydrological Sciences Journal, 55(2): 139-144.

Clayton, H.J., Morris, S.E., McIntyre, N.R., Greaves, M., 2008. The hydrological impact of low-flow alleviation measures. P I Civil Eng-Wat M, 161(4): 171-180.

Cohn, T.A., Lins, H.F., 2005. Nature's style: Naturally trendy. Geophysical Research Letters, 32(23). L23402

Dai, A., Qian, T., Trenberth, K.E., Milliman, J.D., 2009. Changes in Continental Freshwater Discharge from 1948 to 2004. Journal of Climate, 22(10): 2773-2792.

Dixon, H., Lawler, D.M., Shamseldin, A.Y., 2006. Streamflow trends in western Britain. Geophysical Research Letters, 33(19). L19406.

Dixon, H., 2010. Managing national hydrometric data: from data to information. In: Servat, Eric; Demuth, Siegfried; Dezetter, Alain; Daniell, Trevor, (eds.) Global Change: Facing Risks and Threats to Water Resources. Wallingford, UK, IAHS Press, 451-458. (IAHS Publication, 340).

Dong, B.W., Sutton, R.T., Woollings, T., 2011. Changes of interannual NAO variability in response to greenhouse gases forcing. Climate Dynamics, 37(7-8): 1621-1641.

Ekstrom, M., Fowler, H. J., Kilsby, C. G. & Jones, P. D. (2005) New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and impact studies. J. Hydrol. 300, 234–251.

Fleig, A.K., Tallaksen, L.M., Hisdal, H., Hannah, D.M., 2011. Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types. Hydrological Processes, 25(7): 1163-1179.

Francis, J.A. and Vavrus, S.J. 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophysical Research Letters, 39, L06801

Gillett, N. P., Graf, H. F. & Osborn, T. J. (2002) Climate change and the North Atlantic Oscillation. In: The North Atlantic Oscillation – Climatic Significance and Environmental Impact (ed. by J. W. Hurrell, Y. Kushnir, G. Otterson & M. Visbeck). AGU Monograph Series, AGU. pp. 193 - 210

Giorgi, F. et al., 2011. Higher Hydroclimatic Intensity with Global Warming. Journal of Climate, 24(20): 5309-5324.

Hannaford, J. and Buys, G. 2012. Trends in seasonal river flow regimes in the UK. Journal of Hydrology, 475, 158 – 174.

Hannaford, J., Marsh, T., 2006. An assessment of trends in UK runoff and low flows using a network of undisturbed catchments. International Journal of Climatology, 26(9): 1237-1253.

Hannaford, J., Marsh, T.J., 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. International Journal of Climatology, 28(10): 1325-1338.

Hannaford, J. and Hall, J. 2012. Flood risk in the UK: evidence of change and management responses. In: Kundzewicz, Z. (Ed). Changes in flood risk in Europe. International Association of Hydrological Sciences - Special Publication 10 (Blue Book series). 344 – 361.

Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., Prudhomme, C., 2011. Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit. Hydrological Processes, 25(7): 1146-1162.

Hirsch, R.M., 2011. A Perspective on Nonstationarity and Water Management. J Am Water Resour As, 47(3): 436-446.

Hisdal, H., Stahl, K., Tallaksen, L.M., Demuth, S., 2001. Have streamflow droughts in Europe become more severe or frequent? International Journal of Climatology, 21(3): 317-333.

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology, 319(1-4): 83-95.

Ineson, S. Scaife, A.A., Knight, J.R., Manners, J.C., Dunstone, N.J., Gray, L.J., Haigh, J.D. 2011. Solar forcing of winter climate variability in the Northern Hemisphere. Nat Geosci. 4, 753-757.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Jenkins, G.J., Perry, M.C., Prior, M.J., 2008. The climate of the United Kingdom and recent trends. Met Office Hadley Centre, Exeter, UK

Jones, P.D., Lister, D.H., 1998. Riverflow reconstructions for 15 catchments over England and Wales and an assessment of hydrologic drought since 1865. International Journal of Climatology, 18(9): 999-1013.

Jones, P.D., Lister, D.H., Wilby, R.L., Kostopoulou, E., 2006. Extended riverflow reconstructions for England and Wales, 1865-2002. International Journal of Climatology 26(2), 219-231.

Kay, A.L., Jones, D.A., 2012. Transient changes in flood frequency and timing in Britain under potential projections of climate change. International Journal of Climatology, 32: 489 – 502.

Kay, A.L., Crooks, S.M., Pall, P., Stone, D.A., 2011. Attribution of Autumn/Winter 2000 flood risk in England to anthropogenic climate change: A catchment-based study. Journal of Hydrology 406(1-2), 97-112.

Kendon, M., Marsh, T., Parry, S., 2013. The 2010-2012 drought in England and Wales. Weather, 68(4): 88-95.

Kingston, D.G., Lawler, D.M., McGregor, G.R., 2006. Linkages between atmospheric circulation, climate and streamflow in the northern North Atlantic: research prospects. Prog Phys Geog, 30(2): 143-174.

Kundzewicz, Z.W., Robson, A.J., 2004. Change detection in hydrological records—a review of the methodology, Hydrological Sciences Journal 49(1), 7-19.

Laizé, C.L.R., Hannah, D.M., 2010. Modification of climate–river flow associations by basin properties. Journal of Hydrology, 389(1-2): 186-204.

Lavers, D., Prudhomme, C., Hannah, D.M., 2010. Large-scale climate, precipitation and British river flows: Identifying hydroclimatological connections and dynamics. Journal of Hydrology, 395(3-4): 242-255.

Lavers, D.A. et al., 2011. Winter floods in Britain are connected to atmospheric rivers. Geophysical Research Letters, 38.

Lavers, D.A., Villarini, G. Allan, R.P., Wood, E.F., Wade, A.J. 2012. The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large scale atmospheric circulation. Journal of Geophysical Research, 117, D02016

Liu, J.P., Curry, J.A., Wang, H.J., Song, M.R., Horton, R.M., 2012. Impact of declining Arctic sea ice on winter snowfall. P Natl Acad Sci USA, 109(11): 4074-4079.

Lockwood, M., Harrison, R.G., Woollings, T., Solanki, S.K., 2010. Are cold winters in Europe associated with low solar activity? Environmental Research Letters, 5(2): 024001.

Lloyd-Huges, B., Hannaford, J., Parry, S., Keef, C. and Prudhomme, C., 2012. Spatial coherence of European Droughts. Stage 1: UK and European Drought Catalogues. Environment Agency Science Report - SC070079/SR1. 66pp.

Macdonald, N., Black, A.R., 2010. Reassessment of flood frequency using historical information for the River Ouse at York, UK (1200–2000). Hydrological Sciences Journal, 55(7): 1152-1162.

Macdonald, N., Phillips, I.D., Mayle, G., 2010. Spatial and temporal variability of flood seasonality in Wales. Hydrological Processes, 24(13): 1806-1820.

Macdonald, N., Werritty, A., Black, A.R., McEwen, L.J., 2006. Historical and pooled flood frequency analysis for the River Tay at Perth, Scotland. Area, 38(1): 34-46.

Macdonald N., (2012), Trends in flood seasonality of the River Ouse (northern England), from archive and instrumental sources since AD 1600. Climatic Change. 110, 901 - 923

Maraun, D., Osborn, T.J., Gillett, N.P., 2008. United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006. International Journal of Climatology 28(6), 833-842.

Marsh, T., Cole, G. and Wilby, R., 2007. Major droughts in England and Wales, 1800 – 2006. Weather 62, 87-93.

Marsh, T.J., Hannaford, J., 2008. The 2007 Summer floods in England and Wales – a hydrological appraisal. Centre for Ecology and Hydrology, 32pp

Marsh, T.J. and Dixon, H. 2012. The UK Water Balance: how much has it changed in a warming world? In: Proceedings of the eleventh national BHS symposium, Dundee, July 2012: “Hydrology for a changing world”. British Hydrological Society. 5pp.

Marsh, T.J., Harvey, C.L. 2012. The Thames Flood Series – a lack of trend in flood magnitude and a decline in maximum levels. Hydrology Research. 43(3): 203-214

Marsh et al. (In preparation). UK national and regional runoff trends 1961-2010. For Hydrological Processes.

B. Merz, S. Vorogushyn, S. Uhlemann, J. Delgado, and Y. Hundecha. 2012. HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series". Hydrology and Earth Systems Sciences Discussions. 9, 1345 – 1365.

McEwen, L.J., 2006. Flood seasonality and generating conditions in the Tay catchment, Scotland from 1200 to present. Area, 38(1): 47-64.

Morris, S.E., Cobby, D.C., Donovan, B., 2012. Developing indicators to detect changes in the seasonality, frequency and duration of medium and high river flows. Water and Environment Journal, 26(1): 38-46.

Murphy, J.M. et al. 2009. UK Climate Projections Science Report: Climate Change Projections. Met Office Hadley Cente, Exeter.

O’Connell, P. E., Ewen, J., O’Donnell, G., Quinn, P., 2007. Is there a link between agricultural land-use management and flooding? Hydrol. Earth Syst. Sci. 11, 96–107.

Pall, P. et al., 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature, 470(7334): 382-5.

Pattison, I. and Lane, S.N. in press. The relationship between Lamb weather types and long-term changes in flood frequency, River Eden, UK. International Journal of Climatology. DOI: 10.1002/joc.2415

Prudhomme, C., Young, A., Watts, G.Haxton, T., Crooks, S., Williamson, J., Davies, H., Dadson, S., Allen, S. 2012. The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. Hydrological Processes, DOI:10.1002/hyp.8434

Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L., Reynard, N.S., 2010. Scenario-neutral approach to climate change impact studies: Application to flood risk. Journal of Hydrology, 390(3-4): 198-209.

Quinn, N.W. 2010. Are trends in flashiness evident in natural catchments in the United Kingdom? . In: Kirby, Celia, (ed.) Role of Hydrology in Managing Consequences of a Changing Global Environment. British Hydrological Society Third International Symposium. Newcastle, British Hydrological Society,

Radziejewski, M., Kundzewicz, Z.W., 2004. Detectability of changes in hydrological records. Hydrolog Sci J, 49(1): 39-51.

Renard, B. et al., 2008. Regional methods for trend detection: Assessing field significance and regional consistency. Water Resources Research, 44(8).

Robson, A.J., 2002. Evidence for trends in UK flooding. Philos T Roy Soc A, 360(1796): 1327-1343.

Robson, A.J., Jones, T.K., Reed, D.W., Bayliss, A.C., 1998. A study of national trend and variation in UK floods. International Journal of Climatology, 18(2): 165-182.

Stahl, K. et al., 2010. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. Hydrology and Earth System Sciences, 14(12): 2367-2382.

Stahl, K., Tallaksen, L.M., Hannaford, J., van Lanen, H.A.J., 2012. Filling in the white space: recent European runoff trends from WATCH multimodel data. Hydrology and Earth System Sciences, 16, 2035 - 2047

Stott, P.A. et al., 2010. Detection and attribution of climate change: a regional perspective. Wiley Interdisciplinary Review: Climate Change, 1(2): 192-211.

Sutton, R., Dong, B. Atlantic Ocean influence on a shift in European climate in the 1990s. Nature Geosciences, 5, 788 - 792

Svensson, C., Hannaford, J., Kundzewicz, Z.W., Marsh, T.J., 2006. Trends in river floods: why is there no clear signal in observations? Frontiers in Flood Research, Proceedings of Kovacs Colloquium, Paris, June 2006. IAHS Publ. 305, 2006, 12 pages.

Wade, S., Vidal, J-P., Dabrowski, C., Young, P. and Romanowicz, R. 2005. Effect of climate change on river flows and groundwater recharge. A practical methodology. Task 7. Trends in UK river flows: 1970-2002. UKWIR Report CL\04\C\Task7, London pp62.

Watts, G. , Christierson, B., Hannaford, J., Lonsdale, K. Testing the resilience of water supply systems to long droughts in England and Wales. 2012. Journal of Hydrology 414 – 415. 255 - 267.

Werritty, A., 2002. Living with uncertainty: climate change, river flows and water resource management in Scotland. Science of the Total Environment, 294(1-3): 29-40.

Wilby, R.L., 2006. When and where might climate change be detectable in UK river flows? Geophysical Research Letters, 33(19), L19407.

Wilby, R.L., Beven, K.J., Reynard, N.S., 2008. Climate change and fluvial flood risk in the UK: more of the same? Hydrological Processes, 22(14): 2511-2523.

Wilson, D., Hisdal, H., Lawrence, D., 2010. Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections. Journal of Hydrology, 394(3-4): 334-346.