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Trends in seasonal river flow regimes in the UK

J. Hannaford*, G. Buys[1]

Centre for Ecology & Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK.

*Corresponding author: Tel: +44 1491 692234. *E-mail address:* jaha@ceh.ac.uk (J. Hannaford)

[1] Present address: British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK.

Abstract

A wide range of hydrological trend studies have been published for the UK, but there has not previously been a UK-wide assessment of changes in seasonal river flow regimes in a large number of catchments reflecting the diversity of UK rivers. This represents a gap in research, as climate change impacts are likely to vary regionally and seasonally, and seasonal river flows form the basis of many climate change impact assessments. This study attempts to fill this gap, by analysing trends over the 1969 – 2008 period in a network of 89 catchments from across the UK. Many UK catchments are heavily disturbed by human influences, so this study primarily focuses on catchments with near-natural flow regimes, to enable climate-driven trends to be distinguished from direct anthropogenic disturbances such as river regulation and abstractions. Trends are characterised for four standard seasons (Dec – Feb, Mar – May, Jun – Aug, Sep – Nov), for seven flow quantiles. Particular emphasis is placed on examining spatial patterns in observed trend magnitude for median, high and low flows. A set of eight catchments with long records (starting in the 1930s or earlier) are used to assess the representativeness of recent trends in a long-term context, via a moving window trend analysis. The results of this study suggest a much more complex pattern of regional and seasonal variation than revealed in previous work. Some findings resonate with observed rainfall changes, and also with potential future climate change – e.g. increased runoff and high flows in winter and autumn, and decreased flows in spring. The latter is a result which is sensitive to study period, and is not observed in longer records. In summer, there is no compelling evidence for a decrease in overall runoff or low flows, which is contrary to trajectories of most future projections. Overall, the results do not suggest immediate concern for current water resource management on the basis of observed trends alone: however, the differences between observations and model projections suggest these findings should not be viewed complacently, and greater reconciliation between data- and model-based assessments should be sought as a basis for informing water management decisions. The spatial heterogeneity of observed trends (in the lowlands of southeast England especially) suggests caution is needed in extrapolating from small catchments to large regions; understanding this heterogeneity is a major topic for future research.

KeyWords: Trends, River Flow Regimes, Climate Change, High Flows, Low Flows, Natural Catchments, UK

1. Introduction

Globally, there is growing evidence that anthropogenic climate change is intensifying the hydrological cycle (Huntington, 2006). Whilst the evidence for climate change impacts related to increasing temperatures is generally held to be unequivocal, and certain precipitation changes have been attributed to anthropogenic forcing (e.g. Stott et al., 2010), the evidence for climatic-driven trends in river flow regimes is far less compelling, as reflected in the lack of clear signals in historical observations and a lack of consensus in future projections made by climate models (e.g. Svensson et al., 2006; Wilby et al., 2008). There is a growing need, therefore, for observation-based studies that seek to detect and interpret any emerging trends in river flows. Such analyses can be used as a baseline, against which the outputs of climate models can be evaluated in order to achieve a greater reconciliation between the outcomes of data-driven and model-based studies of climate change (Wilby et al., 2008). The characterisation of emerging trends is also a necessary precursor to the development of policy initiatives which may be required to inform mitigation or adaptation strategies.

In the extensive international literature on trends in river flows, changes in seasonal river flow regimes have been widely reported, for example in: the USA (e.g. Novotny and Stefan, 2007; Hodgkins and Dudley, 2006); Canada (e.g. Khaliq et al. 2009; Burn et al., 2010); Switzerland (Birsan et al., 2005); the Nordic region (Wilson et al., 2010); and the Czech Republic (Fiala et al., 2010). Some studies have focused solely on changes in seasonal mean flow, whereas others have attempted to examine changes in seasonal extremes, i.e. low flows (e.g. Fiala, 2010; Khaliq et al., 2009) or floods (e.g. Petrow, 2009). Whilst changes in seasonal flow regimes have been detected, the evidence for any anthropogenic climate change signal is tentative at present. The evidence for temperature-driven changes, such as changes in seasonality reflecting changes in snowmelt timing, is generally more convincing than for precipitation-driven changes in humid environments but, in the latest Intergovernmental Panel on

Climate Change (IPCC) assessment of observed change, evidence for any anthropogenic climate-change influence on river flow regimes was much less compelling than for other indicators of environmental change (Trenberth et al., 2007).

In the UK, there have been several nationwide assessments of seasonal changes in precipitation and other climatic variables (e.g. Jenkins et al., 2008; Maraun et al., 2008) but assessments of seasonal river flows are more limited, with most trend studies analysing indicators of flow at an annual resolution (Robson et al., 1998; Hannaford and Marsh, 2006; 2008). Studies of seasonal change have generally focused on individual catchments (e.g. the Scottish Dee; Baggaley et al., 2009) or particular regions, e.g. Wales and west Midlands (Dixon et al., 2006) or the Severn uplands (Biggs and Atkinson, 2011). Two notable regional studies have addressed the seasonality of flood regimes, in Scotland and northern England (Black and Werrity, 1997), and Wales (MacDonald et al. 2010). Jones et al. (2006) and Wilby (2006) examined seasonal runoff changes over a long time period (1865 – 2002), but used synthetic flow records reconstructed from rainfall, for 15 catchments in England and Wales only. Laize and Hannah (2010) examined seasonal river flow regimes across the UK, but focused primarily on relationships with climate variables and atmospheric circulation. A parallel study to the present paper (Marsh et al. in preparation) considered seasonal trends in runoff records aggregated to large regions of the UK.

The absence of a systematic appraisal of trends in observed seasonal river flow regimes, in a large number of catchments representing the wide range of climatic, topographic and geological characteristics seen across the UK, remains an important gap in research. For policymakers, it is vital that individual seasonal changes are elucidated, as they may counteract one another, meaning that important changes are not detected at the annual scale. Furthermore, seasonal changes can be critical for different aspects of water management: in the UK, summer is the season with the most sensitive balance between supply and demand, so decreases in summer river flow would have obvious implications for water availability; however, drier winters may result in decreased groundwater recharge and reservoir replenishment, increasing the vulnerability of water resource systems to multi-season droughts (Marsh et al., 2007). Conversely, wetter autumn and winter conditions could lead to enhanced flood risk during the main seasons for flooding in many parts of the UK (Black and Werrity, 1997).

The most recent outputs from the UK Climate Projections initiative (UKCP09; Murphy et al., 2009) suggest the UK will experience wetter winters and hotter, drier summers in future. Hydrological modelling studies indicate this will translate to changes in flow regimes, with decreasing flows in summer, increases in winter (e.g. Arnell, 2011; Prudhomme et al., 2012), and increases in flood frequency and magnitude in some regions (Arnell, 2011; Kay and Jones, 2012; Bell et al., 2012).However, considerable uncertainty surrounds most projections – the ensemble-based UKCP09 scenarios lead to a wide range of possible future realisations of monthly and seasonal flows (Prudhomme et al., 2012; Christierson et al., 2012). Projections also suggest an increase in variability which may mean substantial departures from these overall trends in future years. The vulnerability of the UK to such variations has been emphasised by a notable hydrological volatility in the recent past. In apparent conflict with expectations of future climate change trajectories, droughts in 2004 - 2006 (Marsh et al., 2007) and 2010 – 12 (Marsh, 2012) have been caused by successive very dry winters, whilst a sequence of extremely wet summers occurred in the 2007 – 2012 period (e.g. Marsh and Hannaford, 2008). These anomalies illustrate the capricious nature of the UK climate, and emphasise the need to examine seasonal variability in detail.

The aim of this study is to characterise change in seasonal river flow regimes across the UK, across the full range of flows, including indicators of both high and low flows. Two different datasets are used, a network of near-natural catchments, which are generally small and have short (average 45 years) records, and a set of complementary long records from large catchments, which are used to place the more recent trends in a long-term context. An appraisal of trends in seasonal river flow regimes will provide an up-to-date assessment of recent hydrological change, in greater spatial and temporal detail than previously published. It is hoped this will be of benefit to the research community and water managers alike, in documenting recent trends in seasonal water availability and potential changes in flood risk, as well as changes in flow which may be relevant for hydro-ecological management and the implementation of policies such as the Water Framework Directive. The detailed spatial assessment will also provide a robust foundation for comparing with reported model projections, and for validating outputs of historical model runs.

The paper is organised as follows. Firstly, a description of the dataset is provided, followed by the methodology. A results section follows, which considers trends in overall seasonal regimes (via trends in seven flow quantiles), before a discussion of regional patterns in the results. A section then presents the results of trend analyses applied over a range of time periods to the long hydrometric records. The following section is a discussion of the results, specifically addressing possible implications of the findings for water resources management and flood risk management, and putting the results in the context of climate change. Finally, the limitations of the study and avenues for future research are discussed before the paper concludes.

2. Datasets

All daily mean river flow data were obtained from the UK National River Flow Archive (NRFA) (Dixon, 2010), which is the primary UK focal point for hydrometric data. A listing of the Benchmark catchments, and full period-of-record flow data for a substantial majority of the catchments used in this study can be downloaded free of charge from the NRFA website at the following link: http://www.ceh.ac.uk/data/nrfa/index.html

2.1 Benchmark Catchments

One of the reasons for ambiguities in the evidence for climate variability from historical records is the confounding effect of other, more direct, human disturbances – e.g. withdrawals of water for public water supply or irrigation, storage behind impoundments – known to affect river flow across the globe (e.g. Vorosmarty and Sahagian, 2000). Burn et al. (in press) therefore discuss the importance of 'Reference' networks of near natural catchments, which enable climate-driven changes to be distinguished from the noise of anthropogenic disturbances. To this end, the UK 'Benchmark' network, defined especially for this purpose (Bradford and Marsh, 2003), and used in several recent trend studies (Hannaford and Marsh, 2006; 2008), was used in the present study. The benchmark network also enables good geographical coverage of the UK, as it encompasses a wide and representative selection of catchment types. In the present study, only those catchments with a suitable length of record, and that meet certain completeness criteria (discussed below), were used: a total of 89 sites.

2.2 Long hydrometric records

In order to provide a fuller picture of historical variability in seasonal river flows, a number of long hydrometric records were selected from the NRFA. All NRFA records extending back to the 1930s or earlier were considered, but the majority of long records are unsuitable due to having large quantities of missing data or discontinuities. Whilst it is acknowledged that other longer records exist (e.g. reconstructed records, Jones et al. 2006; flood chronologies, MacDonald, 2012), this study deliberately focuses on the widely-available, directly observed daily river flow data held on the NRFA.

The final selection of eight catchments adopted for this study is listed in Table 1 and shown in Fig. 1. Naturalised data were used for the Thames and the Lee (see Marsh and Hannaford, 2008 for information on flow naturalisation), the only two sites with long-term, continuous naturalised records in the UK. All gauging stations have > 70 year records and drain large catchments (over 1000 km^2), meaning they provide an effective contrast to the short records from small Benchmark catchments. However, the geographical extent of the available records is limited, with the available catchments mostly in lowland England and parts of upland Wales. It should be noted that in all UK long records, flow regimes are more likely to be influenced by human disturbances, and may suffer from hydrometric inadequacies and a lack of homogeneity: they are clearly less reliable for detecting climate-driven trends than Benchmark catchments. Nevertheless, the records used are indicative of long-term runoff patterns and were thus deemed suitable for the seasonal flow assessments employed in this study, based on the metadata published by the NRFA (see above). However, they were not used for the assessment of low flows due to known regulation influences.

2.3 Data preparation and infilling

All river flow records are subject to quality control checking before loading onto the NRFA database, which includes validation of data by comparison with analogue catchments, appraisal of extreme high and low flow events and correction or removal of periods of measurement error - see Dixon(2010), for details. For a number of the records, unavoidable periods of missing data are present. For the purpose of this study, data completeness is important; hence, infilling of periods of missing data was undertaken using the equipercentile approach, which has been shown to perform well in an intercomparison of 15 different infilling methods (Harvey et al., 2012). Gaps of less than three days were not considered to be important for the computation of the variables used in this study. For all stations which had gaps of between 3 and 31 days in length an attempt was made to identify a donor station to be used in the infilling process. Where no suitable donor could be found, no infilling was undertaken – in total 17 stations were infilled. If gaps could not be infilled, or more than 31 days was missing in any one year, the year was rejected as a missing year. Following the above data infilling and preparation, any records with more than four years missing (or three continuous) between 1969 and 2008 were excluded from the analysis. Of the 144 Benchmark catchments, 42 were removed due to having too short a record, and 13 were rejected due to not meeting these completeness criteria.

2.4 Seasonal river flow regimes in the UK

Seasonal river flow indicators were computed for the following widely-used monthly groupings endorsed by the UK Meteorological Office: winter (Dec – Feb), spring (Mar – May), summer (Jun – Aug) and autumn (Sep – Nov).

To illustrate seasonal river flow regime variability in UK catchments, Fig 2 shows hydrographs for six different Benchmark catchments representative of a range of river types. The location of these catchments is shown in Fig 1, and characteristics are presented in Table 2. UK river flow regimes can be considered temperate precipitation/evapotranspiration dominated (pluvial), rather than snowmelt (nival) dominated. The seasonal cycle is driven by evapotranspiration, leading to higher flows in winter and lower flows in summer, as shown across the catchments (except the Lambourn), with the spring and autumn as transition months. The three wet, responsive upland catchments conform to the same general pattern, but the Dee has higher spring flows. In this catchment, as in many parts of the Scottish highlands, spring snowmelt from mountainous areas can be a major regime component, whereas it is less important in the other upland sites. Contrasts between the lowland catchments are primarily a reflection of geology: the heterogeneous geology of lowland England dictates marked spatial variations in the responsiveness of flow regimes. The Harper's Brook and Great Stour both have a substantial proportion of impermeable substrates, leading to a direct runoff response to the seasonal climate cycle. In contrast, the Lambourn is a highly permeable (Chalk) catchment with a runoff regime dominated by groundwater storage – it therefore displays a lagged response, peaking in winter/spring, with a minimum flow in the autumn.

2.5 Study Periods and hydrological indicators

Most trend analyses adopt a fixed study period, in order to allow comparisons to be made between sites. For the Benchmark catchments, where the aim is to examine regional patterns of change, a fixed 40-year study period was used, from 1969 – 2008. This represents the trade-off between network coverage and record length which is a feature of most trend studies (Burn et al. in press); the density of the network decreases rapidly with longer periods. No stations with suitable record length were available from Northern Ireland, so sites with records from 1972 were included, to enable coverage in this region. For the long hydrometric records, an alternative approach was used to examine trends across a range of timescales, as detailed in the following methodology section.

For each of the seasonal groupings used in this study, annual time series were derived for the following widely-used hydrological indicators, which represent the whole flow range: mean; Q95; Q90; Q70; Q50 (median); Q30; Q10; Q5. Q*n* is the flow threshold exceeded *n*% of the time. Q95 (Q5) and Q90 (Q10) are therefore indicators of low (high) flow. The median (Q50) provides an indicator of overall seasonal flow. In addition, the seasonal mean flow was computed, as seasonal average flows are widely used in water research and management. Each indicator is calculated for each year, for each season: that is, the Q95 flow was calculated for the spring of 1969, 1970, 1971 and so on up to 2008; and separately for the summer, autumn and winter for all of these years. The same approach was applied to each of the flow thresholds listed above, leading to seven Q*n* time series, plus a time series of the mean flow, for each season.

3 Methodology for Trend Analysis

Assessments of change in hydrological datasets typically employ statistical significance testing to detect trends. Whilst significance testing is an important aspect of formal detection and attribution, there are many factors which must be considered in interpreting statistical significance, e.g. choice of testing method, impact of multi-decadal variability, serial and spatial correlation, long-term persistence. Trend testing is therefore a contentious area, and the literature abounds with discussions on the utility (or otherwise) of statistical tests for trend (see Svensson et al., 2006; Clarke, 2010; Burn et al., in press, for reviews). Furthermore, Wilby (2006) argues that climate change signals may be obscured by low signal-to-noise ratios in historical datasets, which means that climate change may be exerting an effect which is not *detectable*, in a formal statistical sense, but still influential on long-term water resources planning. As the aim of this study is to examine patterns in historical records which may be influential for water management, this study focuses on trend magnitude and direction rather than statistical significance. Considering all trends rather than just those above an arbitrary significance threshold allows a fuller assessment of regional patterns and tendencies. This follows the approach taken in European-wide studies of streamflow trends (Stahl *et al*., 2010; 2012), which can be consulted for a fuller discussion of issues associated with statistical significance testing.

Trend magnitude over the fixed 1969 – 2008 period was assessed using the Thiel-Sen (Sen, 1968) non-parametric estimator of slope, a widely used method for characterising trends. As described in e.g. Stahl et al. (2010), a linear equation was developed from the time series of annual streamflow indicators y with time t as:

$$y = mt + b \qquad (1)$$

where m is the slope and b is the intercept. The slope m was calculated as the median of all slopes m_k of consecutive pairs of values:

$$m_k = \frac{(y_j - y_i)}{(t_j - t_i)} \qquad (2)$$

where k = 1, 2, . . , n(n -1)/2; i = 1, 2, . . , n - 1; and j = 2, 3, . . , n.

The Thiel-Sen slope was fitted to each time series, and the trend magnitude was computed. In order to allow comparison between sites, the trend magnitude for each site was expressed as a percentage of the long-term average value of the indicator under consideration. This allows trends to be compared directly between catchments, which have a very large range in mean flow. This approach was found preferable to expressing a percentage change over the whole record (a widely used alternative) which can sometimes give anomalously high increases when the start values in a series are very low relative to overall variability within the series.

The results for the benchmark catchments were plotted on maps, using catchment boundaries to provide some indication of how representative the river flow trends are of a wider area. Many of the benchmark catchments are small (a necessary response to the need for a near-natural signal), which implies they may be less representative of the surrounding region. As some very small catchments would not be visible on the maps, circles were used to indicate the trend magnitude for catchments less than 50km^2.

For the long-record stations, an alternative approach was used, whereby trends are fitted to moving windows rather than a fixed study period, a technique previously employed by Wilby (2006). Trend estimates were fitted to periods with fixed end points (at the record end, in 2008) and start years varying from the start of the record, and each year thereafter, up to 1988; records of under 20 years length were not considered as short periods are more likely to be influenced by oscillations within the time series (Svensson et al., 2006; Chen and Grasby, 2009). Within each window, the Mann-Kendall (MK)(Kendall, 1975) trend test was applied, and the values of the Mann Kendall *Z* trend statistic were plotted in a time series (with the value referring to the starting year of the window). This indicator is used as an alternative to the Thiel-Sen estimator of slope; steeper slopes are more likely in shorter records, so Thiel-Sen values increase markedly for windows towards the end of the series.

4 Results

4.1 Trends in seasonal flow thresholds in the Benchmark Network

Barplots detailing the percentage of stations in various trend magnitude categories (with -10% to 10% of change assumed to reflect “no trend”) are shown in Fig. 3. These plots show the variability of trend magnitude, across each flow indicator for each season. In addition they highlight how much information is masked when only considering mean annual flow, relative to the more detailed seasonal assessment which is the main focus of this study.

In winter there is a distinction between patterns of trends at high and low flows. There are roughly even percentages of positive, negative and no trend at the low flow range, whereas for higher flow thresholds the proportion of positive trends increases relative to negative trends. In the low flow range, most trends are relatively weak (between 10 – 30% of long-term average, LTA) and there is only a small proportion in the steepest categories (both > 50 % and < -50 %); in contrast, in the high flow range (above Q30) ten percent of stations have positive trends > 50 % of LTA, and there are no negative trends in the highest category.

Of all the seasons, spring exhibits the highest percentage of negative trends across all flow indicators, and the proportion of decreasing trends is greatest at low flow. However, even in the low flow range, negative trends are evident in less than half of the catchments, and the majority of the trends are rather weak, with only a few trends being < - 50% of LTA at Q95 and in the mid-range of flows. As flow increases the number of positive trends increases while the negative trends decrease, but it is not until the two highest flow thresholds that the number of positive trends outweigh the negative.

Summer has the least variation in trend percentages over the flow range. As for winter and spring, the number of positive (negative) trends increase (decrease) with higher flows, but the difference is very subdued in comparison, and the overall proportions appear stable between indicators. Similarly to spring, the number of positive trends > 50 % is consistent through the flow range, but there are more trends in the 30 – 50% category. The proportion of negative trends is similar across the thresholds, with mostly weak negative trends (only a few trends < -50 % are evident, in the lowest two flow thresholds).

Autumn is the season in which the greatest number of positive trends is evident. In the high flow range close to 80 percent of the stations show positive trends, almost half of which are 30 – 50% of LTA, and even at low flows the proportion of positive trends is high. There are very few negative trends, especially at higher flows, and they are weak at low flows. As well as having the greatest number of positive trends overall, autumn has the greatest number of positive trends > 50 % of LTA, and it is the only season where no stations have a trend of < -50 % of LTA in any of the flow indicactors.

In each season the percentage of stations in each trend category is shown for the mean flow, which is a commonly-used seasonal flow statistic in the literature. In summer the bar for the mean flow is fairly similar to that of Q50. However, in winter and autumn the trend partitioning for the mean flow is closer to that of Q30 than the median. Finally for spring the percentage of stations showing no trend is far greater for the mean than for any other flow measure. These differences are because river flow has a skewed distribution and the mean is inflated by the contribution of highest flow values. Hence if only the mean is analysed, any trends detected are more representative of changes to high flows than changes to the flow regime as a whole. The median (Q50) is therefore used in the remainder of this study as an estimator of “medium” range flows and overall changes to the seasonal regime.

In comparison to the seasonal plots, the annual plots do not show the same consistent increase (decrease) in positive (negative) trends with increasing flow. At the low flow range more positive trends are present in the annual record than any of the individual seasons and in the high flow range the partitioning appears to be a mixture of that from winter, spring and summer. Finally for annual mean flow approximately half of the stations fall into the 30 – 10 % range, a high proportion in comparison to any of the seasons. It is clear that trends in indicators of annual flow mask much complexity in the dynamics of flow within the year: seasonal trends of opposing direction can compensate for each other at the annual scale. The pattern of annual flow trends is somewhat different from what would be expected given a straightforward aggregation of the seasonal pattern. Undoubtedly this is due to some cancelling out between inter-seasonal trends, and is also confounded by marked regional contrasts which are discussed in more detail in section 4.2..

In order to put the seasonal changes into context relative to one another, Fig 4 illustrates the pattern of changes for high (Q5) and low (Q95) flows for the six case study Benchmark catchments introduced earlier. The plots show that the contrasting changes observed between seasons on a UK-scale can also be seen within individual catchments. The upland catchments (Dee, South Tyne, Teifi) show a predominance of increasing trends across most seasons, for both high and low flows. However, there are some deceases; flows on the Scottish Dee increase across the seasons, particularly autumn and winter high flows, yet show a decrease in spring high flows. The Teifi shows a decrease in winter low flows, despite high flow increases, and increases in both high and low flows for other seasons. For the South Tyne, high flows increase substantially in winter, but remain unchanged in other seasons; low flows increase in winter and autumn, whereas there is limited change in spring and summer. The lowland sites also show complex inter-seasonal changes. Increased flows are also prevalent for the Harper's Brook, in all seasons except spring, which shows negative trends; substantial low flow increases occur in the other seasons, and notable high flow increases in autumn and winter. Negative trends are more apparent at the other two sites. The Lambourn shows an increase in both high and low flows in winter, contrasting with substantial decreases in summer; spring low flows also decrease, and autumn remains broadly unchanged. A similar pattern is seen for the Great Stour, which shows the greatest decreases of the six sites: the only increase is for winter high flows, contrasting with substantial spring and summer decreases (especially for low flows).

4.2 Regional Patterns of Trends in benchmark catchments

In addition to the variation in trend partitioning between the seasons there is also a high degree of spatial variability in trends. Figures 5, 6 and 7 show maps of trend for each season for Q50, Q95 and Q5 respectively.

The Q50 maps (Fig. 5) show a general northwest - southeast gradient, with largely positive trends in the northwest and a much more mixed pattern in the south and east. Scotland and northwest England are dominated by positive trends throughout the seasons. Across the rest of England and Wales, there are stronger contrasts between seasons: in spring, negative trends dominate (with some strong negative trends in small catchments) and in autumn, positive trends dominate; whilst winter and summer show mixed patterns of generally weak trends (except in the south west and Wales in summer). Two of the Northern Irish catchments show positive trends in all seasons except winter; however, the other catchment has negative trends in all seasons apart from summer.

The low flow (Q95, Fig. 6) maps show different spatial patterns to the Q50 maps – notably, the northwest/ southeast divide is only as pronounced in summer. In winter, in contrast with the Q50 findings, the majority of the catchments in western areas exhibit negative trends, several of which are < -30 % of LTA. Conversely, positive trends in winter are seen in north Scotland, Northern Ireland and the east of England with some strong positive trends in the English Midlands. There is a notable contrast between negative trends further west and positive trends in rain-shadow areas to the east. In spring, the majority of trends are negative, especially in the central and eastern England, although a majority are weak; there are also a substantial number of catchments showing no trend – for example, large catchments in the north of England. The spatial pattern of low flow trends in summer is broadly similar to that of the Q50 trends, although for low flow there are isolated cases of steep negative trends. In autumn the majority of trends are positive with negative trends only occurring in a few small catchments.

The high flow (Q5, Fig. 7), maps show the greatest number of positive trends overall. In winter, catchments in Scotland, Northern Ireland and northwest England exhibit positive trends, which are often strong. Negative trends are confined to small catchments in the east of England and rain shadowed catchments along the border of England and Wales and in northeast England. In spring generally positive trends in the north and west contrast with mixed, but mostly negative, trends in the lowlands of the southeast. Summer shows a similar pattern to spring, although with fewer negative trends and more strong positive trends especially in southwest England and Northern Ireland (reflecting the Q50 results). Autumn has only three catchments with negative trends and the highest number of strong positive trends, across all seasons and indicators. In the southwest and the Welsh borders, and extending through the Midlands to East Anglia, the strong positive trends are especially regionally coherent and there are also strong positive trends in northeast England and east Scotland.

Generally, there is good agreement between the observed patterns and published maps of rainfall trends (Jenkins et al., 2008) showing change over the 1961 – 2006 period. For both rainfall and river flow, the strongest increases in winter are found in the uplands in the north and west. The patterns for spring are also 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 there are no regionally coherent patterns towards decreasing summer flow. The different study periods may be influential here; 2007 and 2008 were wet summers, and were not included in the rainfall analysis 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 Q50 and high flow trends. 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 decrease in summer flows despite significant warming (Jenkins et al., 2008). Further consideration is given to these findings in the discussion below (Section 5).

The regional patterns of high and low flows can also be compared with previous work. An overall tendency towards increasing high flows is supported by observed increases in heavy precipitation; several studies have reported such increases to be greatest in winter, relative to decreases in the summer (Maraun et al., 2008), which are prevalent especially in upland areas (e.g. Burt and Ferranti, 2012). The trends also agree with previous findings from streamflow analysis of increasing high flows in upland, western areas (Hannaford and Marsh, 2008). However, seasonal patterns have generally not been elucidated previously: Biggs and Atkinson (2011) report increasing winter high flows in upland mid-Wales, whilst Dixon et al. (2006) report autumn and winter increases in Wales and the west of England. The present study adds much greater detail on a nationwide scale, and shows important differences between seasons, particularly the contrast between the spatial patterns in winter and autumn. The results also reveal that, on a localised scale, increasing high flows are more prevalent across the UK, in parts of southern England included, than suggested by previous studies.

There are no studies of seasonal low flows with which to compare, but the lack of any coherent patterns in annual low flows reported by Hannaford and Marsh (2006) may partly reflect the wide regional and seasonal differences observed herein. An unexpected characteristic of the low flow analysis is the regionally coherent pattern of negative (albeit mostly weak) winter low flow trends occurring in the west, which appears somewhat counter-intuitive given patterns of winter rainfall and higher flows. It is possible that, whilst overall winter runoff has increased, a shift towards more intense rainfall (Maraun et al., 2008) may mean spates are occurring more episodically, interspersed with longer dry spells associated with flow recessions. Summer trends in the English lowlands were not spatially coherent and generally rather weak. In the European-scale analysis of Stahl et al. (2010), which used 36 of the Benchmark catchments, 'summer' (March – November) low flow trends across much of the UK displayed evidence of a decrease over the 1961 – 2004 period, which contrasts with the mixed pattern shown herein. This reflects different study periods: the 1960s were comparatively wetter, and 2003 and 2004 were dry; whereas the current study ends in 2008, following two very wet summers. This sensitivity to study period further underlines the weak nature of these low flow trends.

The spatial pattern of trends at the annual scale is presented in Fig. 8. There is a clear majority of positive trends over all three flow statistics, with few negative trends that are mainly confined to the Midlands and south. There are more negative trends at the low flow range than the high flow range, although this progression is far less obvious than in the seasonal analysis. Vital information about the variation in trend over the year is lost with the annual analysis, especially in the south of the country where catchments often have negative trends in spring and summer but positive trends in autumn and winter.

4.3 Sensitivity of trends to study period: Long hydrometric records

The results of the moving window trend tests on the long record stations are shown in Fig. 9. Each catchment is plotted as a line representing the variation in Z-statistic in moving windows from each start year to the end of the series, and the results are split by season and flow statistic.

In winter, trends in median flow are generally positive, although only strong for the Scottish Dee, and relatively consistent in time, with the exception of the Avon which has a distinct change from a positive to a negative trend in the mid 1950s. The high flow trend patterns are similar, but there are more negative trends from early start years and, in addition to the Scottish Dee, the Wye also shows consistently strong positive trends. Overall, the results show that winter high flow trends tend to be stable and generally lacking trend (except for the Wye and Dee), whereas there is a shift towards weaker trends in the median although most trends remain positive. In autumn, long-term trends in the median are also largely positive for all records and periods, although in most cases there is a shift towards weaker trends over time (e.g. in the Thames and the Lee). For some catchments, trends are mostly negative (but fairly weak), e.g. the Severn and Welsh Dee. The Avon and Ouse have the strongest positive trends – both are located in central England, where positive trends dominate in the Benchmark analysis, although trends become weaker in more recent windows. In the high flow range all rivers have a pattern of increasing trends for start years up until the 1970s; some start negative and become positive, whilst others become increasingly positive. Post-1970, trends remain positive although become weaker.

The results from the long records demonstrate that recent changes in Benchmark network Q50 and high flows for the winter and autumn are generally representative of longer-term patterns, with the steepest changes generally being for northern and western catchments in winter, and central England for autumn, where recent changes are most pronounced. Previous studies have noted increases in winter runoff in long reconstructed records extending back to 1865 (Wilby, 2006). Whilst there is limited evidence for any statistically significant trend in flood magnitude in long-term datasets, a tendency towards increasing high flows in western catchments since the 1940s has been noted in the few long time series which have been analysed for trend (Hannaford and Marsh, 2008), and Marsh and Harvey (2012) found a positive high flow trend in the >130 year Thames record, although no significant upward trend in flood peak as measured by instantaneous annual maximum.

In spring the trends are coherent between stations for the median and high flow statistics over the full analysis period. Overall there is a consistent pattern across both indicators of positive trends for early start years decreasing to negative trends from the 1960s onwards (followed by a slight increase in magnitude, but with a majority of post 1965 trends being negative). The results attest to a marked regime shift, from largely positive to negative trends. Baggaley et al. (2009) found an overall increase in spring flow in the Scottish Dee, and a recent decrease (since 1980), both consistent with the long record trend observed herein, and attributed the decline to a decreasing contribution from snowmelt relative to rainfall. This is undoubtedly a feature of many upland catchments, but the recent decrease in the Dee is much steeper than for other long records. Whether changing snowmelt patterns explain the consistent decreases seen in the wide range of stations is an area for future research (discussed further in section 5) – particularly in the English lowlands where snowmelt plays a lesser role in runoff generation, although historically its role may have been greater. Interestingly, a strikingly similar shift in spring flows is seen in a comparable analysis conducted by Murphy et al (in review) for near-natural catchments with long records from Ireland – the congruency between these findings suggests large-scale atmospheric circulation changes may be responsible.

Up until the 1960/70s, summer trends across both flow indicators vary greatly between stations, whereas from the 1969 start year of the above analyses, trends are mostly consistent and neutral. For Q50, trends from 1969 were mostly positive, whereas in earlier start dates there is a contrast between positive trends, occasionally strong (e.g. The Ouse, Avon and Welsh Dee) and negative trends (in the Severn and Scottish Dee). A broadly similar pattern follows for Q5. The Ouse has especially strong positive trends up until the 1970s in the median flow statistics. Other stations show a mixture of positive and negative trends in median and high flows with a tendency for lower magnitude trends for more recent start years. A general lack of strong or consistent summer trends was also found in the reconstructed records analysed by Wilby (2006).

5 Discussion

5.1 Implications for water resources management

One of the most interesting features to emerge from this study is the change in winter flow regimes, with a contrast between increasing high flow and decreasing low flow trends in the west. The winter half-year is a crucial time for water resources management in the UK, as the season when upland reservoirs and lowland groundwater reserves are replenished. In the uplands, the observed shift towards moderate decreases in winter low flows is compensated for by increasing high flows which would ensure overall winter replenishment would be unaffected (as shown by a lack of trend in winter Q50 flows). However, the shift towards decreased winter low flows and increased high flows – i.e. an amplified range – could have consequences for instream ecology, by being less favourable to aquatic wildlife adjusted to a particular range of flows (Richter et al., 1997). Winter recharge is vital for replenishing aquifers in the southeast of England, and many historic droughts are associated with dry winters (Marsh et al., 2007). The results suggest a very mixed pattern in winter flows in the southeast: the lack of any coherent trend towards decreasing winter flows suggests no cause for immediate concern, but localised winter decreases warrant further investigation.

From a water resources perspective, the tendency towards lower spring flows is a potentially important result. Spring can be a critical period for late replenishment of water resources, and dry spring conditions are a contributor to notable deficits in many drought episodes (e.g. Marsh et al., 2007). Spring is a crucial time in the life cycle of aquatic fauna (e.g. for salmonid incubation, Solomon and Lightfoot, 2007), so a tendency towards decreasing flows could have ecological consequences. However, it should be noted that the tendency towards decreasing spring flows is not seen in longer periods, following a change-point around 1960. Whether the recent spring decline reflects anthropogenic warming (via a reduction in snowmelt or an increase in evapotranspiration), or step-change resulting from changes in atmospheric circulation, or a combination of both, is an open question (see section 5.3). From a water management perspective, addressing this question will be vital for establishing whether decreasing spring runoff is likely to continue in the near future.

Summer flow trends exhibit very mixed patterns, but generally positive trends outweigh negative trends, which appears a favourable position for water resources. The UKCP09 scenarios project decreasing summer rainfall (Murphy et al., 2009) for much of the UK, and catchment modelling studies suggest this will lead to pronounced decreases in summer river flows (Prudhomme et al. 2012; Christierson et al., 2012) and low flows, particularly in southern England (e.g. Arnell, 2011). On the basis of the results 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 (Christierson et al. 2012). However, the overall increase in summer shrouds important regional differences: in the English lowlands there are some decreasing trends and these are occasionally strong (notably for some small catchments at low flows). Sensitivity to study period further underlines that a lack of decreasing trends in summer, or low flows more generally, should not be viewed too complacently: summer rainfall trends up to 2006 show a moderate decrease (Jenkins et al., 2008), whilst Stahl et al. (2010) reported decreasing low flows up to 2004. The presence of two wet summers (2007 and 2008) at the end of the flow series are likely to be influential in determining the more mixed pattern reported herein. Notwithstanding these caveats, the lack of coherent change in summer, in either the Benchmark records or the long series, is somewhat different from that expected under climate change, and a much more confused picture emerges. In contrast, decreases in summer are one of the more consistent results (albeit with a wide range of magnitudes) from the latest probabilistic modelling studies (e.g. Prudhomme et al., 2012; Christierson et al. 2012).

The years following the 2008 end date of this study further testify to the apparent lack of congruency between expected patterns of change and observations. 2010 – 2012 was characterised by a severe drought, driven by successive dry winters, followed by one of the wettest summers on record (Marsh, 2012). A pattern of drier winters and wetter summers has been remarkably prevalent from 2007 and further calls into question the assumptions of dry summer/wet winter trajectories of future change. The cause of these patterns is an active area of research: cold, dry winters in northern latitudes may be driven by fluctuations in solar activity (Ineson et al. 2011), whilst decreasing sea-ice extent, as a result of anthropogenic warming, may also be behind shifts in the jet stream (Francis et al. 2009) which have been associated with the anomalously dry winters and wet summers. Understanding these emerging patterns is clearly vital for water management, and observational datasets, such as those used herein, can provide a foundation for such initiatives.

5.2 Implications for flood management

The recent past has seen a number of large-scale, damaging flood events, several of which have not conformed to typical seasonal patterns. Autumn and winter are the dominant flood season in the UK, especially in the west (Black and Werritty, 1997). Major winter half-year floods have occurred in recent years (e.g. in 2000, 2005 and 2009) but a series of notably wet summers also occurred in the 2007 – 2012 period, with major flooding occurring in many of these years (e.g. Marsh and Hannaford, 2008) . The results of the present study provide a context within which to examine whether these events are part of any emerging trends in seasonal high flow regimes (although the prevalence of wet summers in the years after this study means this question will need to be revisited in future updates). Overall, the analyses suggest little reason to suspect that recent events betray any marked changes in high flow seasonality. Trends were strongest in winter and autumn, and there is a general contrast between increasing trends in the north and west, in all seasons, and a much more mixed pattern in the southeast. Whilst this echoes the findings of previous studies, the new results give much greater detail: for example, the steepest increases in winter high flows occur in upland catchments in the north, but steep high flow increases in winter can also be observed across southern England. The southwest and Midlands show strong, regionally coherent increases in autumn.

The results suggest a shift towards increased high flows, which has parallels with studies of extreme rainfall (see section 4.2) – taken together, such findings may be suggestive of enhanced flood risk which, if sustained, would have consequences for engineering design and the assumption of stationarity which underpins flood estimation methods (Robson et al., 1998). However, a previous study in the Benchmark network suggests caution is needed in extrapolating from trends in high flows to any trend in extreme floods: many catchments with increasing high flow duration and frequency did not have an equivalent trend in flood magnitude (Hannaford and Marsh, 2008). Whilst the results presented herein suggest little evidence for major changes in seasonality, the contrasting results between seasons, and across various parts of the UK, suggest that detailed studies of trends in flood frequency and seasonality are required. MacDonald et al. (2010) analysed 30 Welsh flood records for changes in seasonality over time, but no marked shifts in seasonality were found. A similar approach applied at a UK scale may show changes in frequency/seasonality relationships.

There are some parallels between observed trends in 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, attributing the trends identified in the Benchmark network is a challenge. The trends are sensitive to the study period used, with the early 1970s recognised as a relatively quiescent period for flooding (Robson et al. 1998; Hannaford and Marsh, 2008) relative to the 1990s/early 2000s. This reflects changes in atmospheric circulation patterns, notably a shift to a more prevalent positive North Atlantic Oscillation Index (NAOI) in winter from the 1960s to the early 2000s – an influence on UK winter climate that has been associated with extreme rainfalls (e.g. Maraun et al., 2011), winter runoff (Laize and Hannah, 2010) and high flows (Hannaford and Marsh, 2008). The pronounced increase in winter flows reported herein may partly reflect this upward trend in the NAOI, but the present study shows that high flows have increased in other seasons (the strongest increases in high flows were shown for autumn, when the connection with the NAOI is less apparent) and in parts of the south less strongly influenced by the NAO. A downturn in the NAO since the mid-1990s has led to some strongly negative NAO winters in the recent past – as discussed in Section 5.1, solar variations and sea-ice may be influencing north Atlantic climate variability, with potential implications for high flows.

Other temperature-driven changes may also be influencing high river flows. It is likely that snowmelt has become less influential in the UK as a flood generating mechanism, as temperatures have increased over the post-1930 period of this study, an assumption that is borne out by modelling studies (e.g. Kay et al. 2011). 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. As discussed in section 4.2, the spring high flow trends in the mountainous Scottish Dee catchment may reflect a diminishing role of snowmelt relative to rainfall (Baggalley et al. 2009). Unfortunately, there are relatively few observational studies of changes in snowmelt flooding. 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.

5.3 Limitations of trend tests and directions for future research

Along with many previous studies, there are some parallels with expected patterns of climate change, but also important differences. 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. Future modelling studies are inevitably subject to large uncertainties, whilst observational studies are subject to a range of limitations in the data and methodologies used. This study has attempted to overcome these limitations as much as possible, by using a network of catchments with near-natural regimes and good quality data.

Nevertheless, there are important caveats which must be applied when assessing the results of any study of observed trends, as discussed below.

Wilby et al. (2008) point out that low signal-to-noise ratios mean that changes may not be statistically detectable above the noise of natural variability. The current study does not use statistical significance but trend magnitude may be also be influenced by high variability and persistence (i.e. clusters of below/above average years). The last decade, in particular, has seen notable droughts and high flow periods, which must be borne in mind when considering the results. An even more pressing question is whether trends in any fixed study period are representative of longer-term variability (Kundzewicz and Robson, 2004; Chen and Grasby, 2009). In the present study, sensitivity to study period has been considered by a moving window analysis in long records, which shows that some results (e.g. spring trends) are different from what may be expected if longer records are used, owing to inter-decadal variability. Future work is required to characterise this variability and determine if it is linked to teleconnections such as the NAO – as conducted for step-changes in North American runoff, for example, which were attributed to the Pacific Decadal Oscillation (Woo et al., 2006).

In assessing the lack of congruency between observed flow trends and climatic observations (as well as potential future changes), it is important to consider the role of contrasting responses from different catchment types. This study is necessarily broad-scale, and seeks to analyse 89 catchments, with a diverse range of properties – which may be expected to respond very differently to the same climatic variations. Heterogeneous patterns in seasonal trends are particularly notable in the south-east, and may reflect the influence of groundwater in this area. Groundwater storage introduces a lag between climate and streamflow response (see section 2.4): permeable catchments could therefore be responding out-of-phase relative to more responsive sites. A number of studies have shown that responsive catchments in the west show stronger links with climate drivers (such as weather types and the NAO) than catchments in the southeast, (Laize and Hannah ,2010; Fleig et al., 2011), largely because of groundwater storage lags in the southeast. Prudhomme *et al*. (2010) and Jackson et al. (2011) demonstrate that the sensitivity of catchments to future climate change also depends on the properties of catchments and aquifers. Ongoing work by the authors is therefore seeking to examine the heterogeneity of observed seasonal trends in the English lowlands, in connection with observed trends in groundwater levels.

A further issue with the current study is the relatively small size of Benchmark catchments (median catchment area <100km^2) – other authors have highlighted the fact that small reference network catchments may not be representative of larger scales (Burn et al., in press). Nevertheless, the results from this study accord well with a parallel analysis of national runoff trends (Marsh et al., in preparation), which examines trends in time series representing total runoff (assembled from aggregating runoff from large catchments) from Britain and its component parts.

Whilst this study has attempted to control the effect of human influences by using the Benchmark network, they cannot be fully ruled out, and may also account for some of the observed heterogeneity. Land-use and land cover change is also a potential driver of flow trends. Catchments with known major land cover changes were filtered from the Benchmark network, but rural land use has changed significantly across most of the UK since the Second World War. Whilst previous reviews have shown that evidence for land use change impacts on flood regimes is inconclusive and generally not detectable in catchments larger than 10km^2 (O' Connell et al., 2007), recent studies have found changes in flow regime characteristics linked to land-use change in larger catchments (e.g. over 200km^2; Archer et al., 2010). A major follow-up project by the study authors is attempting to investigate the relative role of climate and land use signals in a range of UK catchment types.

6 Conclusion

Climate change could influence seasonal runoff patterns, but many previous studies of observational streamflow trends focus on annual indicators. The present study, for the first time, examines changes in seasonal flow regimes across the whole of the UK, and thus provides an improved characterisation of recent hydrological change for the scientific community and policymakers.

The results of this study have demonstrated variability in seasonal flow regimes over the last 40 years, in catchments with near-natural flow regimes free from major anthropogenic disturbances, with the direction and magnitude of change varying regionally, between the seasons, and across the range of flows – with distinct differences between patterns of high and low flow trends. The analysis of long records enables these results to be placed in a fuller historical context.

The main findings of the study, by season, were:

- An overall increase in winter river flows, with the largest increases in northern catchments; whilst high flows increased in the western uplands, low flows decreased in some western catchments, suggesting an increased winter range. Long records suggest winter trends over the last 40 years are broadly representative of longer periods
- A tendency towards lower spring flows in lowland England, with a regionally coherent decrease in spring flows, across the flow range. However, long records indicate that this is feature of post-1960 records, and all long records showed an increase in spring flow from the 1930s to present, with a transition to negative trends from around 1965.
- A very mixed pattern of results for summer – with generally increasing summer flows in the north and west (which were occasionally strong in some catchments), contrasting with a very mixed pattern of (primarily weak) positive and negative trends in the English lowlands. Long records also show a very mixed pattern between catchments.

- Strong evidence for an increase in autumn flows, across the flow range, which was particularly coherent for high flows for central and southwest Britain and northeast Scotland. Long records suggest these changes are broadly representative of long-term increases in autumn.

Some observed trends (increasing winter flow range, decreasing spring flows) may be influential for water management and could be ecologically significant, and the tendency towards higher flows may reflect a generalised increase in flood risk. Overall, however, the predominance of increasing flow trends across the seasons, coupled with limited decreases in low flows, is favourable from a water management perspective. Nonetheless, there are pronounced regional contrasts, and localised decreasing trends warrant further investigation. A fuller investigation of seasonal peak flows is also required to determine the extent to which high flow trends reflect any changes in the frequency or magnitude of extreme flows. Other key results are the very mixed spatial pattern of trend responses (particularly in the English lowlands) and the extent to which some recent trends are not representative of longer-term change. Further work is required to understand the causes of this spatial and temporal heterogeneity, and the findings suggest caution is needed in extrapolating river flow changes (whether observed past or projected future) from individual catchments and fixed study periods.

This study has presented results which have some parallels with climate change projections, but has also shown results which seem inconsistent. The use of a reference network of near-natural catchments implies the observed trends reflect climate drivers, but it is not possible to conclude whether anthropogenic warming underlies these changes, owing to the relatively short records and confounding role of multi-decadal variability. Nevertheless, the lack of any obvious tendency towards decreasing river flows (for summer and for low flows especially) is in apparent contrast to expectations for the relatively near future under climate change scenarios. Given the observed exceptional increase in UK temperature (and compelling evidence for an anthropogenic contribution, e.g. Stott et al., 2010), the lack of decreasing river flows may reflect some degree of resilience to anthropogenic warming.

Clearly, improving reconciliation between models and observations should be a continuing focus of research in the UK. Detection and attribution studies, which have recently been applied to river flows (Pall et al., 2011; Kay et al. 2011), hold some promise for identifying anthropogenic signals from noise. Other studies have explicitly used observed trends as a tool for validating model outputs (McCabe and Wolock, 2011; Stahl et al., 2012). Good quality data from catchments with near-natural regimes and long hydrometric records will play a vital underpinning role in providing "ground truth" for such modelling studies in future.

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TABLES

Table 1 Selected metadata for the catchments with long hydromeric records used in this study. To differentiate between the two Dee catchments, 'S' refers to the Scottish river and 'W' to the Welsh river. "n" in the NRFA ID column denotes a station with naturalised data. Metadata from Marsh and Hannaford, (2008).

NRFA ID	River	Name	Start Year	Catchment Area (km^2)	Mean annual rainfall (mm)	Baseflow Index	10th percentile elevation (m)	Median Altitude (m)	90th percentile elevation (m)
12001	Dee (S)	Woodend	1929	1370	1122	0.53	193	508	805
28085	Derwent	St Mary's Bridge	1936	1054	1007	0.63	111	262	413
33002	Ouse	Bedford	1933	1460	654	0.53	64	101	139
38001 (n)	Lee	Fieldes Weir	1883	1036	643	0.59	64	99	137
39001 (n)	Thames	Kingston	1883	9948	720	0.63	50	100	182
54001	Severn	Bewdley	1921	4325	924	0.53	69	127	359
54002	Avon	Evesham	1936	2210	668	0.52	52	96	147
55002	Wye	Belmont	1935	1896	1248	0.46	114	296	469
67015	Dee	Manley Hall	1937	1013	1415	0.53	157	347	499

Table 2 Details of the six case study catchments used to illustrate seasonal flow regimes.

Metadata from Marsh and Hannaford, 2008

NRFA ID	River	Site Name	Start Year	Catchment Area (km^2)	Mean annual rainfall (mm)	Baseflow Index	10th percentile elevation (m)	Median Altitude (m)	90th percentile elevation (m)
12001	Dee (S)	Woodend	1929	1370	1122	0.53	193	508	805
23004	South Tyne	Haydon Bridge	1962	751	1175	0.34	184	333	550
62001	Teifi	Glan Teifi	1959	894	1377	0.39	108	195	333
32003	Harper's Brook	Old Mill Bridge	1938	74.3	638	0.48	57	90	121
39019	Lambourn	Shaw	1962	234	742	0.96	118	166	206
40011	Great Stour	Horton	1964	345	759	0.70	40	75	146

FIGURE CAPTIONS

NB Figures can be viewed online http://www.sciencedirect.com/science/article/pii/S002216941200861X

Figure 1	Location of the long record catchments used in this study, and the six case study catchments shown in Figure 2 and discussed in section 2.4. Grey shading shows land over 200m to broadly differentiate upland areas.
Figure 2	Examples of seasonal river flow regimes for six case study Benchmark catchments. The mean monthly flows are plotted as a solid black line, whilst the range for each month is plotted as grey lines
Figure 3	Barplots showing the proportion of trends in various magnitude categories (expressed as a proportion of the long-term mean of the indicator in question), for the mean flow and seven flow thresholds, for each season and for annual averages.
Figure 4	Changes in seasonal high (Q5) and low (Q95) plotted for the six case study Benchmark catchments. The seasonal long-term averages (LTA) for Q5 and Q95 over the 1969 - 2008 period are shown as circles (black = Q5, red = Q95). The trend (% change) resulting from the trend over the 1969 – 2008 period, as applied to the LTA, is shown as crosses. The shaded areas show the range +/- 1 standard deviation from the LTA. Where the ranges overlap, a dashed line shows the lower bound of the Q5 range. No lower bound is shown for the Harper's Brook for autumn Q5 , due to high skewness causing a negative value
Figure 3	Maps showing the spatial variation in trends in median, Q50: trends are shown in various categories, based on the magnitude of the trend expressed as a percentage of the long-term mean value (according to legend)
Figure 4	Maps showing the spatial variation in trends in low flows, Q95: trends are shown in various categories, based on the magnitude of the trend expressed as a percentage of the long-term mean value (according to legend)

Figure 5	Maps showing the spatial variation in trends in high flows, Q5: trends are shown in various categories, based on the magnitude of the trend expressed as a percentage of the long-term mean value (according to legend)
Figure 6	Maps showing the spatial variation in trends for annual averages of Q50, Q95 and Q5: trends are shown in various categories, based on trend magnitude as a percentage of the long-term mean (according to legend)
Figure 7	Results of moving window analyses applied to long hydrometric records, for each season and for Q50 and Q5. The results show the Mann-Kendall Z statistic applied in moving windows, from all possible start years (up to 1988) to the end of the series. The Z-statistic is plotted at the start of the moving window. Colours correspond to those used in Fig 1.