UK seasonal river flow variability in near-natural catchments, regional outflows and long hydrometric records

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Abstract

This paper presents an assessment of changes and variability in seasonal river flows in the UK, using three complementary datasets spanning different periods and spatial scales: (1) 95 small, near-natural catchments, 1969–2008, (2) regional outflows for large areas of the UK, 1961–2008 and (3) eight major catchments with records from pre-1940 to 2008. The most notable patterns to emerge are an increase in winter and autumn river flows in some regions, which appear to be robust, spatially and temporally. Spring and summer trends were generally much weaker, spatially very variable, and in both these seasons the directionality of trends changes over the course of the longer records. Overall, the results suggest stability in seasonal mean flows — with limited evidence for changes which are of significance for water management — but reveal much complexity in the temporal and regional patterns, which warrant detailed investigation in future. This work provides a baseline of seasonal river flow variability against which emerging changes and model projections can be assessed.

Introduction

Globally, there is growing concern that anthropogenic climate change is intensifying the hydrological cycle, which may be expected to influence river flow regimes. Whilst the evidence for many climate change impacts related to increasing temperatures is unequivocal, and certain precipitation trends have been attributed to climate change (Stott *et al.,* 2010), the evidence for climatic-driven shifts in river flows is far less compelling, as reflected in the lack of any clear signals in historical observations (e.g. Svensson *et al.,* 2006) and a lack of consensus in future projections made by climate models (e.g. Wilby *et al.,* 2008).

One of the reasons for ambiguities in the evidence from historical records is that other, more direct, human disturbances — most notably, withdrawals of water for public water supply or irrigation, storage behind impoundments, and the influences of changes in land management — are also responsible for modifying streamflows across the globe (Döll *et al.,* 2009). For this reason, Hannah *et al.* (in press) argue that studies of climate-driven trends should use networks of near-natural catchments. In the UK, a 'Benchmark' network has been defined for this purpose, and several recent studies have used this network to characterise recent river flow trends. Hannaford and Marsh (2006, 2008) found evidence of increasing annual runoff and high flows in the benchmark network, whilst evidence for trend in low flows was less compelling. Since the period covered by these studies (from the early 1960s to 2003), notable hydrological volatility has been observed in the UK, with an extended drought in 2004–2006 (Marsh *et al.,* 2007) and a sequence of extremely wet summers (e.g. Marsh and Hannaford, 2008).

There have been several national assessments of seasonal changes in rainfall and other climatic variables (e.g. Jenkins *et al*., 2008) but assessments of Benchmark river flow trends have focused on annual indicators. Studies of seasonal change have been limited to individual catchments (e.g. the Scottish Dee; Baggaley *et al*., 2009) or particular regions (e.g. Wales and west Midlands; Dixon *et al*., 2006). Jones et *al*. (2006) examined seasonal changes over a long time period (1865–2002), but focused on synthetic flow records (1865–2002) reconstructed from rainfall, and only considered England and Wales rather than the UK. The absence of a systematic appraisal of trends in observed seasonal river flows across the UK therefore remains an important gap in research. For policymakers, it is vital that individual seasonal changes are elucidated, as different seasons are important for different aspects of water management. Decreases in winter and spring recharge and reservoir replenishment, for example, may increase the vulnerability of water resource systems to multi-season droughts (Marsh *et al*., 2007), whereas wetter autumn and winter conditions could lead to enhanced flood risk. The most recent projections from UK Climate Projections (UKCP; Murphy *et al*., 2009) suggest the UK will experience wetter winters and drier summers in future. However, the 2004–6 winter droughts and the wet summers of the recent past underline 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 and variability in seasonal average river flow across the UK. Firstly, a national picture of climate-driven trends over the last 40 years will be developed by examining changes in natural 'benchmark' catchments. These catchments are generally rather small, and their flow records are short (typically from the 1960s): a wider geographical assessment will be made using regional 'outflow' series; longer-term variability will be addressed with reference to hydrometric records which extend back to the 1930s.

Datasets

All data were obtained from the UK National River Flow Archive: http://www.ceh.ac.uk/data/nrfa/index.html.

Seasonal mean river flows were computed for the following datasets, according to widely-used monthly groupings: winter (Dec–Feb), spring (Mar–May), summer (Jun–Aug) and autumn (Sep–Nov).

- Benchmark catchments: as employed in previous

Table 1 *Details of the gauging stations 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.*

NRFA ID	Name	River	Start Year	Catchment Area (km^2)	Mean Annual Rainfall (mm)	Base Flow Index
12001	Woodend	Dee (S)	1929	1370	1122	0.53
28085	St Mary's Br	Derwent	1936	1054	1007	0.63
33002	Bedford	Ouse	1933	1460	654	0.53
39001	Kingston	Thames	1883	9948	720	0.63
54001	Bewdley	Severn	1921	4325	924	0.53
54002	Evesham	Avon	1936	2210	668	0.52
55002	Belmont	Wye	1935	1896	1248	0.46
67015	Manley Hall	Dee (W)	1937	1013	1415	0.53

analyses by Hannaford & Marsh (2006, 2008). Only those catchments with a suitable length of record (discussed below) were used, a total of 95 sites.

- Regional outflows: as employed in the UK National Hydrological Monitoring Programme (Marsh & Sanderson, 2010). These represent outflows from large-scale regions of the UK from 1961 - present, and are derived from a network of major rivers which, taken together, provide a homogeneous record to runoff patterns at the national scale The following regional runoff records were used: England and Wales, Scotland, and the English Lowlands.
- Long hydrometric records: a selection of records which go back to the 1930s or earlier for the catchments listed in Table 1 and shown in Figure 1. These catchments were chosen as they have gauging stations with > 70 year records and drain large catchments (over 1000 km^2). The flow regimes are more likely to be influenced by human disturbances, and may suffer from hydrometric inadequacies and a lack of homogeneity. Despite these limitations, they are deemed suitable for seasonal mean flow assessments.

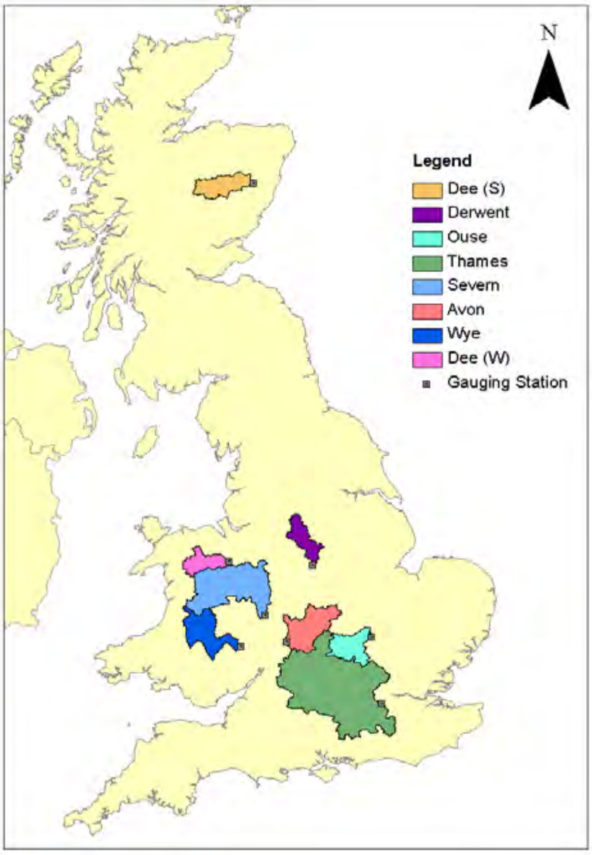

Figure 1 *Location of the long record catchments used in this study.*

Methodology

Historical assessments of change in hydrological datasets generally 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; see Svensson *et al.,* 2006, and Clarke, 2010 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 directionality 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 a European-wide initiative to assess streamflow trends (Stahl *et al.*, 2010).

For the benchmark catchments, a fixed study period of 1969–2008 was used to examine trends. This period is a compromise between an acceptable record length and good regional representativeness of the UK. The period is broadly comparable, but more up-to-date, to previous assessments (Hannaford and Marsh, 2006, 2008). 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.

Trend magnitude over this fixed period was assessed using the Thiel-Sen (Sen, 1968) non-parametric estimator of slope, a widely used method for characterising trends. All station time series were first standardized using *z*-scores (values were subtracted from the mean, and divided by the standard deviation), to permit comparisons between catchments. This means trend magnitude is expressed as a proportion of the standard deviation. The results for the benchmark catchments are 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 50 km^2.

For the regional runoff series, the Thiel-Sen slope was also fitted to the 1969–2008 Benchmark study period, and locally-weighted regression (loess) smoothing was used to show variability (as opposed to trend) over the full period of record, to put the recent benchmark trends in a more detailed temporal and wider spatial context.

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 moving windows, starting in every year from the start of the record, up to 1978; records of under 30 years' length were not considered as short records are more likely to be influenced by oscillations within the time series (Svensson *et al*., 2006). Within each window, the Mann-Kendall (MK; Kendall, 1975) trend test was applied, and the values of the Mann Kendall 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.

Results

Benchmark catchments

Maps showing the seasonal flow trends in the benchmark network are illustrated in Figure 2

Winter flows have increased across Scotland and northern England, with the steepest trends generally confined to smaller catchments. Positive trends are also apparent in west Wales (although these are weaker), contrasting with

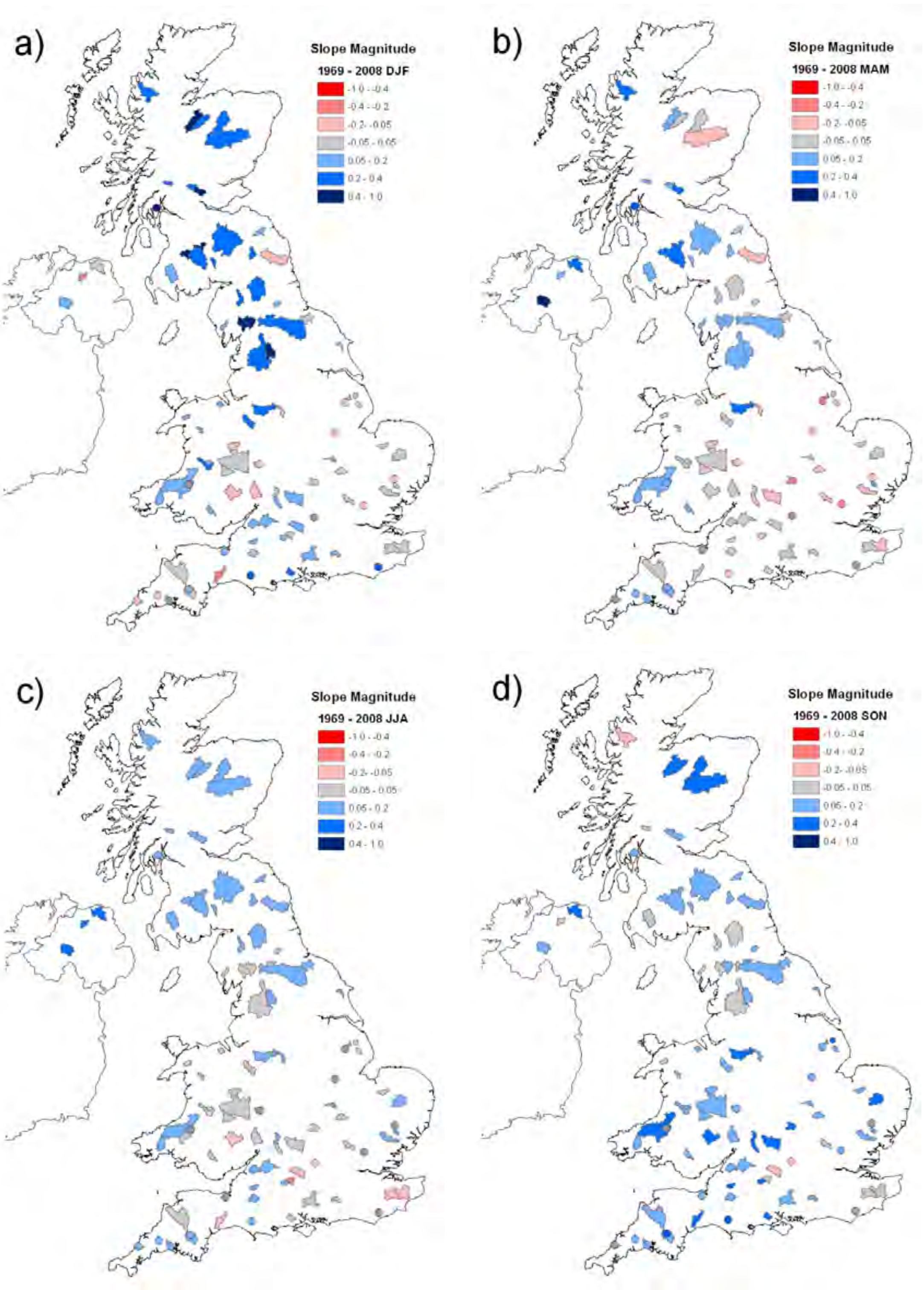

Figure 2 *Results of trend tests applied to the Benchmark Network, 1969 – 2008. a) winter, b) spring, c) summer, d) autumn.*

some negative trends in the Welsh borders. Interestingly, positive winter flow trends are not coherent across the whole Atlantic margin, with mixed patterns in the south-west peninsula. Across lowland England, there is little distinct evidence of trend, although some smaller catchments show some weak declining trends.

In spring, river flows have increased in some northern catchments, but the picture is far more mixed than for winter, and trends are of lower magnitude. In western Scotland, Northern Ireland and catchments in northern England with a westerley aspect, trends are positive but mostly weak; in some north-eastern UK catchments, negative trends are apparent. Further south, patterns are very mixed; weak increases occur in west Wales and parts of south-west England, but in the lowlands, many catchments show declining trends, which are generally weak in all but the smallest catchments.

Summer river flow trends are of much lower magnitude than in other seasons. Summer flows have increased across Scotland and much of northern England, although trends are very weak; steeper increases were observed in Northern Ireland, which may reflect the major flooding in summer 2008 (Marsh and Sanderson, 2010). Across England and Wales, a very mixed picture emerges. Some increases are seen in west Wales and on the south-west peninsula; in contrast, weak decreases occurred in other western catchments (e.g. north Wales). In the lowlands, the picture is equally mixed, with decreasing flow in some catchments in the south-east, and increases in some catchments in East Anglia.

Overall, autumn flows have increased over a significant majority of catchments, with relatively high magnitude trends in many cases. Regionally coherent increases are apparent in the north-east of the UK and across south-west England; from the south-west peninsula and south Wales, and further east into the lower-lying areas of central England. Whilst a mixed picture emerges in the English lowlands, it is notable that there are increases in many eastern catchments, which are occasionally fairly strong.

Regional outflows

Seasonal flow trends for the regional outflow series are shown in Figure 3.

Winter ouflows have increased in all three regions, with by far the steepest trend for Scotland and a modest increase in the English Lowlands. The loess curve shows a downturn later in the Scottish outflow series (reflecting low values in the early 2000s), but the last two very wet winters are consistent with the increasing trend. Whilst some inter-decadal variability is apparent in the loess curves, generally this is modest compared to other seasons.

For spring, outflows exhibit a weak decline for E & W, and a steeper decline for the English lowlands. There is pronounced sub-decadal variability in these series, with lower spring flows in the 1970s and 1990s. In Scotland, spring flows have increased overall, from a low in the early 1970s to a peak in the early 1990s, with generally lower spring flows since then.

Summer outflows have declined in the lowlands, albeit weakly. Generally, there is substantial variability, with higher summer flows early in the period. Low summer flows were common in the mid-1970s and the 1990s, and near the end of the series; the two very wet summers of 2007 and 2008 (Marsh and Hannaford, 2008; Sanderson and Marsh, 2010)

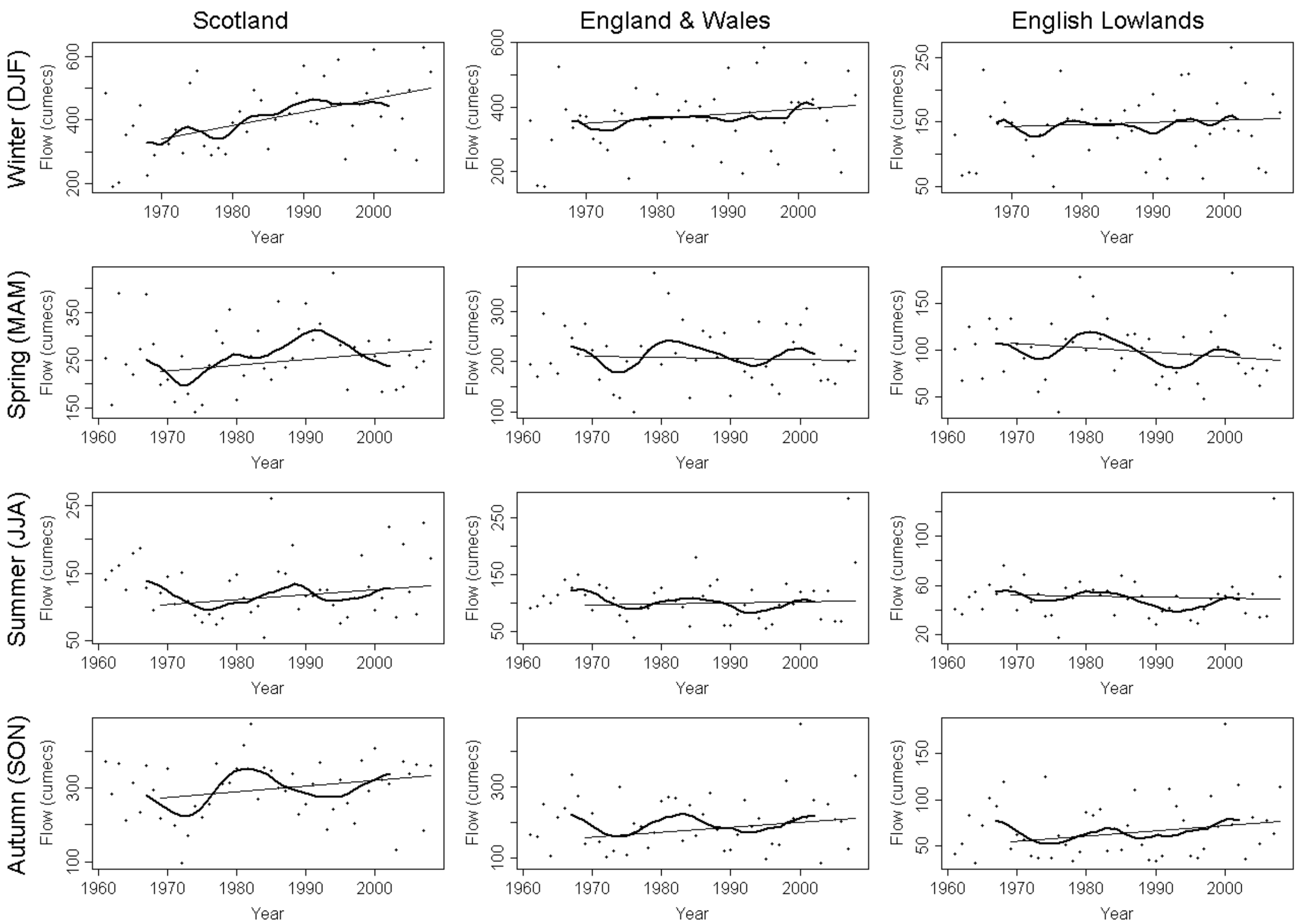

Figure 3 *Plots showing variability in regional outflows for Scotland (S, left), England and Wales (E & W, centre) and the English Lowlands (EL, right).*

undoubtedly affect the trend slope, and a general decline in summer flows is more apparent if these years are ignored. Scotland shows an increase in summer flows, but with lower summer flows in the 1970s and some wet summers later in the series.

The outflows for autumn all display an overall increase, but this is relatively modest and overlies pronounced variability. A notable feature in both the E & W and the English lowland outflows is the outstanding autumn outflow for 2000, associated with major flooding. For the Scotland outflows, there are two particularly dry autumn periods after 2000.

Long records

The results of the analyses for long records are presented in Figure 4.

For a majority of the studied catchments, winter trends are positive through most of the record, and the trends are particularly notable for the Scottish Dee and the Wye (although the trend becomes stronger more recently). Notable positive trends in the Thames, Ouse and Avon from the 1940s have become weaker, and in other catchments there is fluctuation around the zero line.

A notable feature of the spring trends is the coherence of the patterns between all catchments. From pre-1940, most spring trends are positive, but later in the record the strength of the trend diminishes and generally becomes negative from the 1960s. Declining trends were strongest for start dates in the 1960s, and weakened in the 1970s before becoming stronger again just before 1980.

The Thames, Ouse and the Avon show very strong positive summer flow trends from pre-1960 — the droughts of the 1930s and 1940s (Marsh *et al.*, 2007) are likely to be influential. In these three catchments, trend magnitude diminishes, and decreasing trends occur later in the series. In other catchments, negative trends dominate through most of the record, although there is a shift towards more positive trends from the 1960s and 1970s, peaking in the mid-1970s (likely to reflect the influence of the dry early to mid-1970s); this pattern is particularly notable on the Wye, Severn and Scottish Dee.

For autumn, positive trends generally dominate, but the magnitudes are very different. The strongest positive trends are evident through the records for the Ouse and the Avon, and parts of the Scottish Dee and Welsh Dee record. Weaker positive trends are seen in the Thames records, and for other catchments, weak negative trends (strong in the early Severn records) are evident up to the 1960s, with positive trends from the 1970s.

Discussion

Data from the benchmark network show that winter and autumn river flows have increased in many areas of the UK since the late 1960s, and this is strongest and most regionally coherent in the north-west in winter. Previous work has shown increases in winter rainfall (Jenkins *et al.*, 2008), annual runoff and high flows (Hannaford and Marsh, 2006, 2008) in upland western areas. The detailed regional picture in the present study reveals that in some western areas (e.g. Cornwall) winter flow decreased, whilst in Wales and western England there is a gradient from increases in the west to decreases in more sheltered catchments, similar to the results of Dixon *et al.* (2006). In autumn, trends were weaker than in winter, but many more catchments showed increases, which were especially coherent in some areas such as the south-

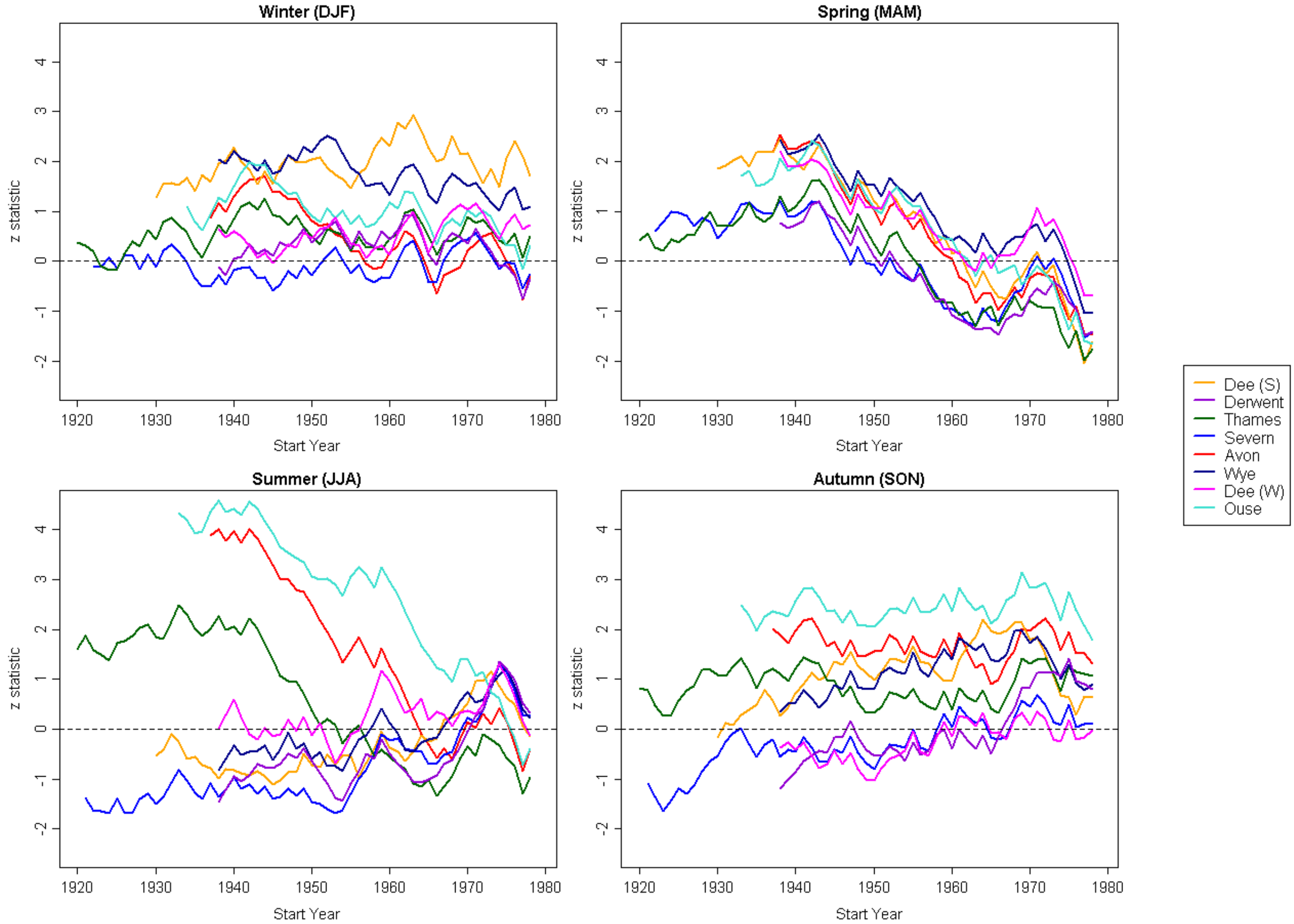

Figure 4 *Moving window trend analyses for long hydrometric records. Key colours correspond to the location map (Figure*

west. The pattern of autumn increases agrees with observed seasonal rainfall changes; Jenkins *et al*. (2008) observed greatest autumn changes in south-central and western England, and north-east Scotland.

The increases in winter half-year flow appear to be robust, geographically and temporally. Positive Dec–Feb winter trends are generally coherent spatially (particularly for Scotland, as evidenced by the national outflows) and temporally, with positive trends extending back through most long records. Whilst there is variability and clustering in the autumn flows, and they exhibit weaker increases (evident from the regional outflows), the tendency towards positve trends in some western and central catchments (e.g. the Wye and the Avon) extends back through the record. The autumn and winter increases observed herein agree with previous work showing increases in winter half-year runoff (Wilby, 2006) in reconstructed records extending back to 1865.

In spring, increases were observed in some northern and western catchments, but negative trends were more apparent in lowland areas (a pattern which broadly agrees with rainfall trends; Jenkins *et al.,* 2008), although most trends were weak. Overall, a weak decrease was observed in England and Wales spring outflows, and an increase in Scotland. The long records show that decreasing spring trends occur in many catchments from the 1960s, but that the directionality of trends changes before this date, with strong positive trends from pre-1940. The summer trend patterns broadly agree with rainfall, with decreases in central England and increases in the far east of England and central Scotland (Jenkins *et al*., 2008), but there are far fewer negative flow trends and they are generally weak. Overall, the long records show that summer flows have decreased in most records over longer timescales, which suggests that the increasing summer trends in some benchmark catchments may not be representative of longer periods. The overall picture for the summer half-year appears to be one of stability. Similarly, Wilby (2006) found summer half-year flow trends were mixed, but with a tendency towards decreasing trends (albeit mostly non-significant) in records from 1865.

The results of this study highlight the importance of examining change at a seasonal level, and also demonstrate the benefit of focusing on trend magnitude, which enables improved assesssment of regional patterns. For example, the present study demonstrates that winter flows decreased in south-west England, but autumn flows increased, which is obscured in the annual signals (a fairly weak overall decrease was reported by Hannaford and Marsh, 2006). Whilst overall patterns are commensurate with rainfall changes, there are clear departures, and very mixed signals emerge in some regions; in isolated cases, neighbouring catchments exhibit trends of opposing directionality. Small-scale differences may reflect localised factors, as catchment characteristics have an important part to play in moderating the effect of regional climate changes (e.g. Laize, 2008). It is noteworthy that the steepest trends often occur in some of the smallest catchments. For winter runoff, this may reflect the fact that documented increases in heavy rainfall are likely to be most influential (Osborn *et al*, 2000) in small, steep, headwater catchments. Land-use changes cannot be ruled out, and have been shown to be influential in parts of upland Britain, although this has primarily been documented in flood response (e.g. Archer, 2007).

The results generally present a picture of hydrological stability: increased winter and autumn flows may suggest heightened vulnerability to fluvial flooding, but there is less solid evidence for any change which is significant in water resources terms. Whilst the trend magnitudes are often very modest, the seasonal patterns are broadly commensurate with changes expected under climate change (increases in winter, decreases in summer and an enhanced northwest–southwest rainfall gradient over the UK). However, the current study suggests patterns of observed seasonal river flow change are far more complex than this simplistic characterisation suggests. Furthermore, it is vital to recognise that changes in atmospheric circulation (particularly the North Atlantic Oscillation, the influence of which has widely been reported elsewhere; e.g. Hannaford and Marsh, 2008) may have been very influential in determining these patterns.

The study has demonstrated the utility of a long-term perspective in interpreting recent trends. Whilst the most compelling trends (autumn and winter increases) are resilient to changes in study period, the tendency towards decreasing spring flows is not apparent in longer records, which suggests a regime shift which is not captured in benchmark records. Whilst the overall trends point to stability, the changing directionality and magnitude of trends in long records emphasises the role of relatively wet or dry epochs, which can be particularly influential for water resources management, especially where multi-year droughts are concerned. The present study has established a baseline of change in mean conditions, whilst changes in variability and in seasonal flow extremes are arguably more important for water managers. This is the subject of ongoing research by the authors, using the benchmark catchments and long records.

Conclusions

This study has analysed a range of datasets to elucidate historical seasonal river flow variability in the UK. Unlike many previous studies, formal significance testing was not applied; rather, trends were assessed in terms of their relative magnitude and directionality, to give a very detailed pattern of regional changes.

The strongest signal to emerge from this study is an increase in winter half-year flows. Regionally coherent winter (Dec–Mar) trends were apparent in northwestern catchments, particularly Scotland. Weaker, but generally coherent autumn trends were seen in western and central England. These trends appear to be resilient to changes in study period. For the summer half-year, trends were weaker (particularly for summer, Jun–Aug) and a very mixed regional picture emerges. Whilst there are some decreasing spring flows in eastern areas, long records show a shift towards more positive trends in longer records; in contrast, summer flows show more pronounced decreases in longer records. Overall, with the exception of the winter increases, the results suggest a broad hydrological stability, with limited evidence for trends which are particularly influential for water management. The approach followed clearly demonstrates the utility of examining natural catchments, along with additional datasets to ensure results are representative of longer time periods, and wider geographical areas. The detailed regional patterns, and extra information added by examining individual seasons, is highly beneficial in providing a 'baseline' of historical change, against which emerging trends can be identified.

References

Archer, D. 2007. The use of flow variability analysis to assess the impact of land use change on the paired Plynlimon catchments, mid-Wales. *J. Hydrol.*, **347**, 487–496.

Baggaley, N.J., Langan, S.J., Futter, M.N., Potts, J.M. and Dunn, S.M. 2009. Long-term trends in hydro-climatology of a major Scottish mountain river. *Sci. Total Environ.*, **407**, 4633–4641.

Clarke, R. 2010. On the (mis) use of statistical methods

in hydro-climatological research. *Hydrolog. Sci. J.*, **55**, 139–144.
Döll, P., Fielder, K. and Zhang, J. 2009. Global scale analysis of river flow alterations due to water withdrawals and reservoirs. *Hydrol. Earth Syst. Sci.*, **13,** 2413–2432.
Dixon, H., Lawler, D.M. and Shamseldin, A.Y. 2006. Streamflow trends in western Britain. *Geophys. Res. Lett.*, **33**, L19406.
Hannah, D.M., Demuth, S., Lanen van, H.A.J., Looser, U., Prudhomme, C., Rees, G., Stahl, K., Tallaksen, L.M. In press. Large-scale river flow archives: importance, current status and future needs. Invited Commentary. *Hydrol. Process*.
Hannaford, J. and Marsh, T.J. 2006. An assessment of trends in UK runoff and low flows using a network of undisturbed catchments. *Int. J. Climatol.*, **26,** 1237–1253.
Hannaford, J. and Marsh, T.J. 2008. high flow and flood trends in a network of undisturbed catchments in the UK. *Int. J. Climatol.*, **28**, 1325–1338.
Jenkins, G.J., Perry, M.C. and 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., Wilby, R.L. and Kostopoulou, E. 2006. Extended river flow reconstructions for England and Wales, 1865 – 2002. *Int. J. Climatol.*, **26**, 219–231.
Kendall, M.G. 1975. *Rank Correlation Methods*. Charles Griffin, London.
Laizé, C.R.L. 2008. Seasonal hydroclimatological variability in near-natural UK river basins. *Proc. British Hydrological Society 10th National Symposium, Exeter.*
Marsh, T., Cole, G. and Wilby, R., 2007. Major droughts in England and Wales, 1800 – 2006. *Weather,* **62**, 87–93.
Marsh, T.J. and Hannaford, J. 2008. *The 2007 Summer floods in England and Wales – a hydrological appraisal.* Centre for Ecology and Hydrology, Wallingford. 32pp
Marsh, T.J. and Sanderson, F.J. 2010. *UK Hydrological Review of 2008.* National Hydrological Monitoring Programme, Wallingford. 25pp.
Murphy, J.M. *et al.* 2009. *UK Climate Projections Science Report: Climate Change Projections.* Met Office Hadley Cente, Exeter.
Osborn, T.J., Hulme, M., Jones, P.D., Basnett, T.A. 2000. Observed trends in the daily intensity of United Kingdom precipitation. *Int. J. Climatol.*, **20**, 347–364.
Sen, P.K. 1968. Estimates of the regression coefficient based on Kendall's Tau. *J. Amer. Statist. Ass.*, **63**, 1379–1389.
Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L.M., van Lanen, H.A.J., Sauquet, E., Demuth, S., Fendekova, M. and Jódar, J. 2010 Streamflow trends in Europe: evidence from a dataset of near-natural catchments, *Hydrol. Earth Syst. Sci. Discuss.*, **7**, 5769–5804, doi:10.5194/hessd-7-5769-2010.
Stott, P.A., Gillet, N.P., Hegerl, G.C., Karoly, D.J., Stone, D.A., Zhang, X. and Zwiers, F. 2010. Detection and attribution of climate change: a regional perspective. *Wiley Interdisciplinary Review, Climate Change*. **1**, 192–211.
Svensson, C., Hannaford, J, Kundzewicz, Z.W. and Marsh, T.J. 2006. Trends in river floods: why is there no clear signal in observations? In: *Frontiers in Flood Research:*