High and low flow trends in a national network of undisturbed indicator catchments in the UK

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Abstract This paper presents the results of trend analyses applied to indicators of high and low flows in a network of undisturbed catchments in the UK, over the 1970–2004 period. Significant positive trends in high flows were identified across northern and western areas; these increases are associated with changing atmospheric circulation patterns associated with the North Atlantic Oscillation (NAO), and may reflect the impact of multi-decadal oscillations rather than climatic change. There was no compelling evidence for any pronounced decrease in low flows, despite the clustering of droughts in recent years. The recent trends are compared to several longer (>60 year) hydrometric records which show pronounced temporal fluctuations, but there is little evidence of long-term trend.

Key words flood(s); high flows; low flows; Mann-Kendall test; natural catchments; North Atlantic Oscillation; trends; UK

INTRODUCTION

It is widely speculated that greenhouse-gas induced global warming will lead to an increase in the severity of floods and droughts in many parts of the world. In the UK, scenario-based Regional Climate Model (RCM) forecasts envisage increases in extreme rainfall (Ekstrom *et al.*, 2005), and possible future impacts on flood frequency (Kay *et al.*, 2006). Similarly, Arnell (2003) presents simulations which project reductions in low flows, and Fowler & Kilsby (2004) report projected increases in drought severity. Hydrological monitoring programmes have an essential part to play in characterising historical variability in order to discern emerging trends in flow regimes—the identification of such trends is a necessary foundation for the development of appropriate water policy and management responses to climate-driven change.

A major obstacle in discerning climatic-driven changes in river flow patterns is the combined impact of anthropogenic disturbances, such as heavy abstraction rates and extensive impoundments. These and the varying hydrometric capabilities of gauging stations—particularly in the extreme flow ranges—may contribute to spurious trends. To overcome these obstacles, a “benchmark” network of 120 near-natural catchments, monitored by gauging stations with good hydrometric performance, has been identified in the UK (Bradford & Marsh, 2003).

This paper presents the results of trend tests applied to indicators of high and low flows for gauging stations in the benchmark network, over the 1970–2004 period. The results are evaluated in the context of possible climatic-driven changes. Finally, a selection of longer records is used to place recent trends in a fuller historical perspective.

DATA

The data used for this analysis are based on daily flow records from the benchmark catchments, derived from the National River Flow Archive at CEH Wallingford. Four variables were used:

(a) annual minimum 30-day flow ($m^3 s^{-1}$);
(b) annual maximum 30-day flow ($m^3 s^{-1}$);
(c) prevalence of low flows (number of days below the 90th percentile flow);
(d) prevalence of high flows (number of days above the 10th percentile flow).

The first two variables were chosen as indicators of low and high flow magnitude, the second two relate to low and high flow duration. For the low flow indicators, calendar years were used. For the high flow indicators, UK water years (1 October–30 September) were used; this limits dependence between high flow events, which frequently occur over the transition between calendar years.

The UK gauging station network expanded rapidly during the late 1960s—consequently, selection of an optimal study period is necessarily a compromise between geographical coverage and available record length. Trend tests were carried out for a 1970–2004 study period, for which 78 Catchments were available. Trend tests are sensitive to the analytical timeframe used (Kundzewicz & Robson, 2000); the implications of this are considered further under "long records".

METHODS

The Mann-Kendall (MK) test (Kendall, 1975) was used to test for trend. Permutation tests, as described by Kundzewicz & Robson (2000), were then used to asses the significance of trends.

Each time series was tested for autocorrelation, which can increase the probability of detecting trends when none are present (Yue *et al.*, 2002). There were relatively few catchments with significant autocorrelation in the indicators: for high flow prevalence, only three river flow series had significant lag-1 autocorrelation, but for low flows, 12 cases were significant. For these cases, a block resampling approach was used; essentially the permutation approach remains the same, but the data are permuted in two-year blocks to preserve the lag-1 autocorrelation (Kundzewicz & Robson, 2000).

A Trend Index (TI, Svensson *et al.*, 2005), was used to summarise results. The TI relates to the significance level, α, of the two-sided test as:

$$TI = 100 - \alpha, \text{ for positive trends, and} \quad (1)$$

$$TI = -(100 - \alpha), \text{ for negative trends} \quad (2)$$

Thus, a negative trend significant at the 10% level will have TI = –90.

RESULTS

High flow trends

The results for the high flow indicators are presented in Fig. 1. Significant positive trends in 30-day maxima and high flow prevalence were identified across northern and western areas—particularly in northern England and southern Scotland. The increases in high flow magnitude and duration are primarily in upland areas exposed to maritime climatic influences, contrasting with lowland areas in eastern England where there are few significant results. The increasing trend in long-duration high flow events in some northern and western areas has some parallels with observed increases in extended-duration rainfall (e.g. for 10-day maxima; Fowler & Kilsby, 2003) and annual runoff (Hannaford & Marsh, 2006).

The increase in high flows in western areas is consistent with changing atmospheric circulation patterns associated with the increasing North Atlantic Oscillation trend observed from the early 1960s until the late 1990s (Wilby *et al.,* 1997). The NAO Index (NAOI) has been shown to be correlated with winter rainfall (Wilby *et al.*, 1997) and runoff (Shorthouse & Arnell, 1999) in maritime areas of Great Britain. In the present study, winter (December–March, DJFM) q10 prevalence was correlated with winter (DJFM) NAOI. The winter season was chosen, as this is when the NAO influence on UK climate is most pronounced (Wilby *et al.*, 1997). The results (Fig. 2) suggest the NAO has an important influence on winter high flows in some maritime catchments. More vigorous westerly airflows in positive NAO years are associated with greater orographic rainfall in upland western areas. Sheltered eastern catchments have negative correlations with the NAO, in common with the analyses applied to runoff by Shorthouse & Arnell (1999). The results suggest the increasing trends in high flows identified in this study may be influenced by a shift towards a positive NAO since the early 1960s. However, many catchments correlated with the NAOI show no significant increasing flow trend (e.g. for northern Scotland, cf. Fig. 1(b) and Fig. 2). Clearly, further work is required to elucidate these relationships in more detail.

An increase in long duration high flow events and the prevalence of high flows could have significant impacts on future flood management. Some RCM analyses predict increases in extended duration rainfall events for northern and western areas (Ekstrom *et al.*, 2005). However, whilst the results of trend tests presented here have some parallels with such scenarios, the

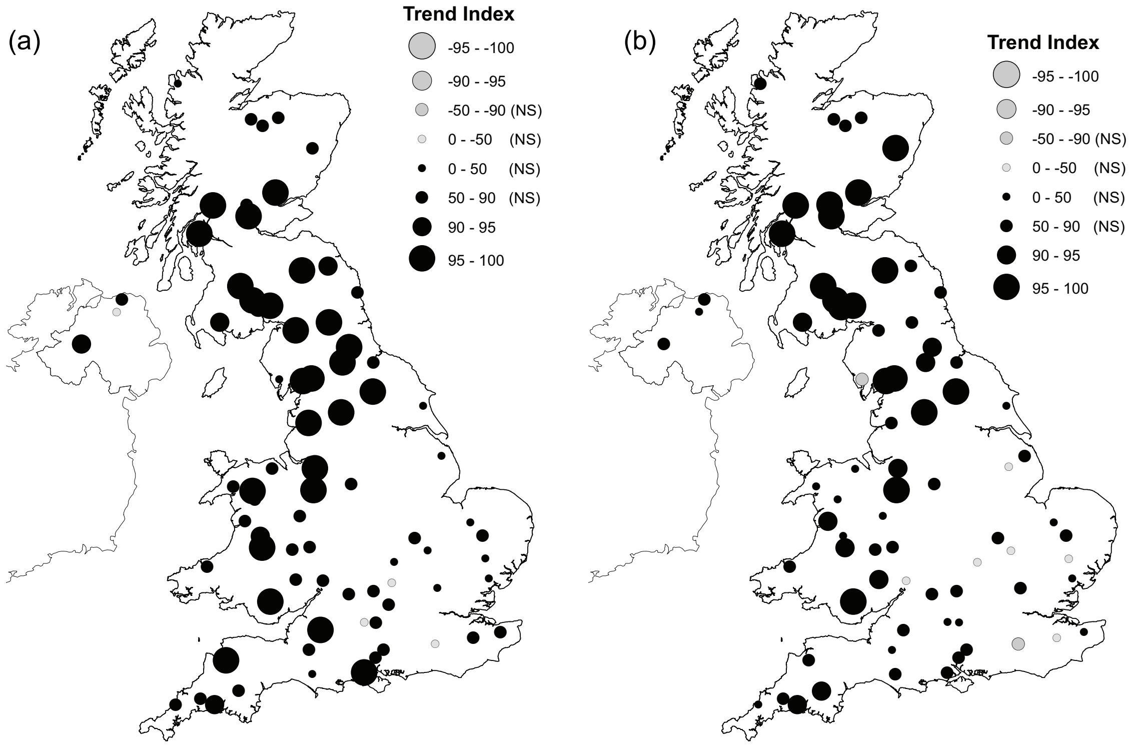

Fig. 1 Results of trend tests for high flow indicators: (a) 30-day maxima, (b) q10 prevalence. Trend Index shown according to legend.

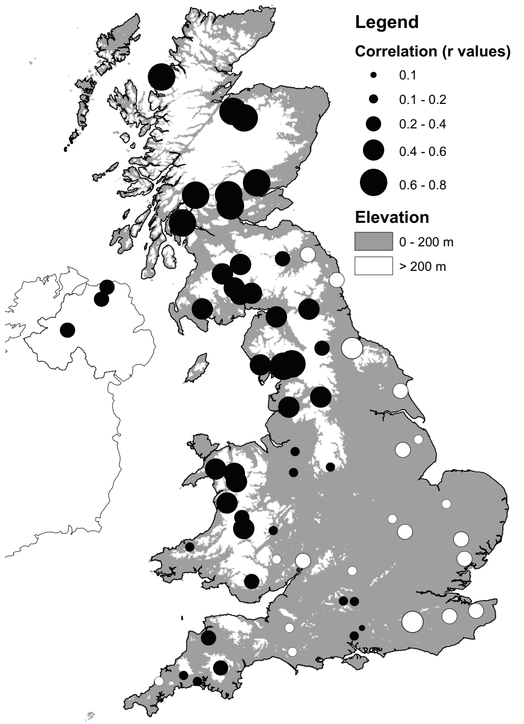

Fig. 2 Correlation between winter q10 prevalence and winter NAOI. Dark graduated circles show positive correlation, white shows negative. Elevation above 200 m is also highlighted.

association with the NAO means that recent trends may reflect multi-decadal oscillations rather than long-term climate change, although the NAO itself may be influenced by climate change (Gillet *et al.*, 2002).

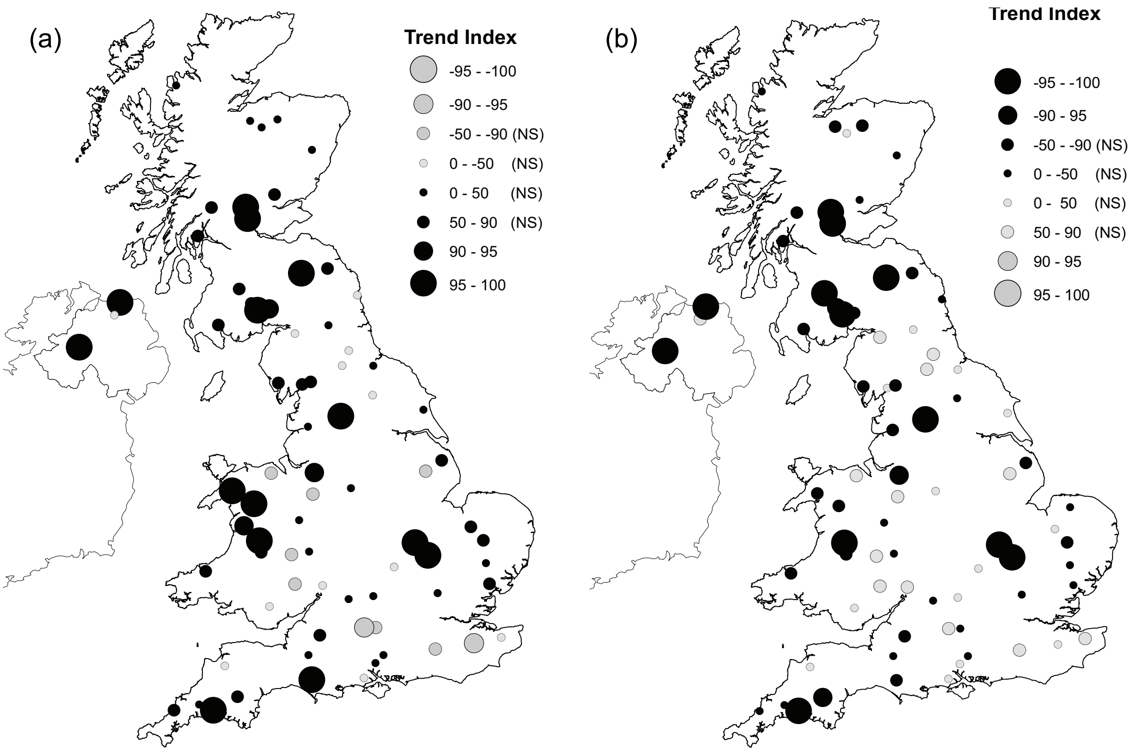

Fig. 3 Results of trend tests for low flow indicators: (a) 30-day minima, (b) q90 prevalence. Trend Index shown according to legend. Note that the prevalence results are reversed to allow comparison with the minima; a positive sign indicates a decrease in the time spent below q90, i.e. suggesting low flows are becoming less severe.

Low flow trends

The results from the low flow analyses are presented in Fig 3. Similarities with the high flow trends can be recognised (e.g. southwest Scotland) but generally the low flow trends display less spatial coherence.

There appears to be a tendency towards decreasing low flows in some southeastern catchments, but few of the trends are significant. This is particularly interesting, considering the clustering of recent drought periods which have impacted heavily in southeast England (e.g. 1988–1992, 1995, 2003). The lack of decreasing trends is not consistent with some scenario-based hydrological modelling forecasts (e.g. Arnell, 2003) which project significant decreases in Q95 flows by the 2020s, particularly for southeastern areas. This lack of congruency may reflect the uncertainties inherent in modeling, such as a possible countervailing effect of multi-decadal variability (Arnell, 2003), as well as the limitations associated with trend tests; e.g. the effect of high inter-annual variability and sensitivity to short record length (Kundewicz & Robson, 2000). With these caveats acknowledged, the observations presented in this study suggests there is little evidence for a pronounced shift towards lower flows or increased low flow duration over the last 35 years.

Long records

Limited record length is typically a major obstacle to interpreting the results of trend analysis, as there are often few homogeneous records on which to base long-term assessments of change. In this study three long hydrometric are used to examine recent trends in a fuller historical context. Figure 4 features high and low flow prevalence (long time series of minima and maxima were similar and are not presented). The Thames catchment is subject to major artificial influences, but naturalized data (Littlewood & Marsh, 1996) are presented here.

Over the longer timescales, a significant (at the 90% level) long-term trend in high flows was only observed for the Wye in Wales (1935–2004). For the Dee (Scotland), the long-term trend is non-significant, but the locally weighted regression (LOESS) smoothing suggests marked temporal

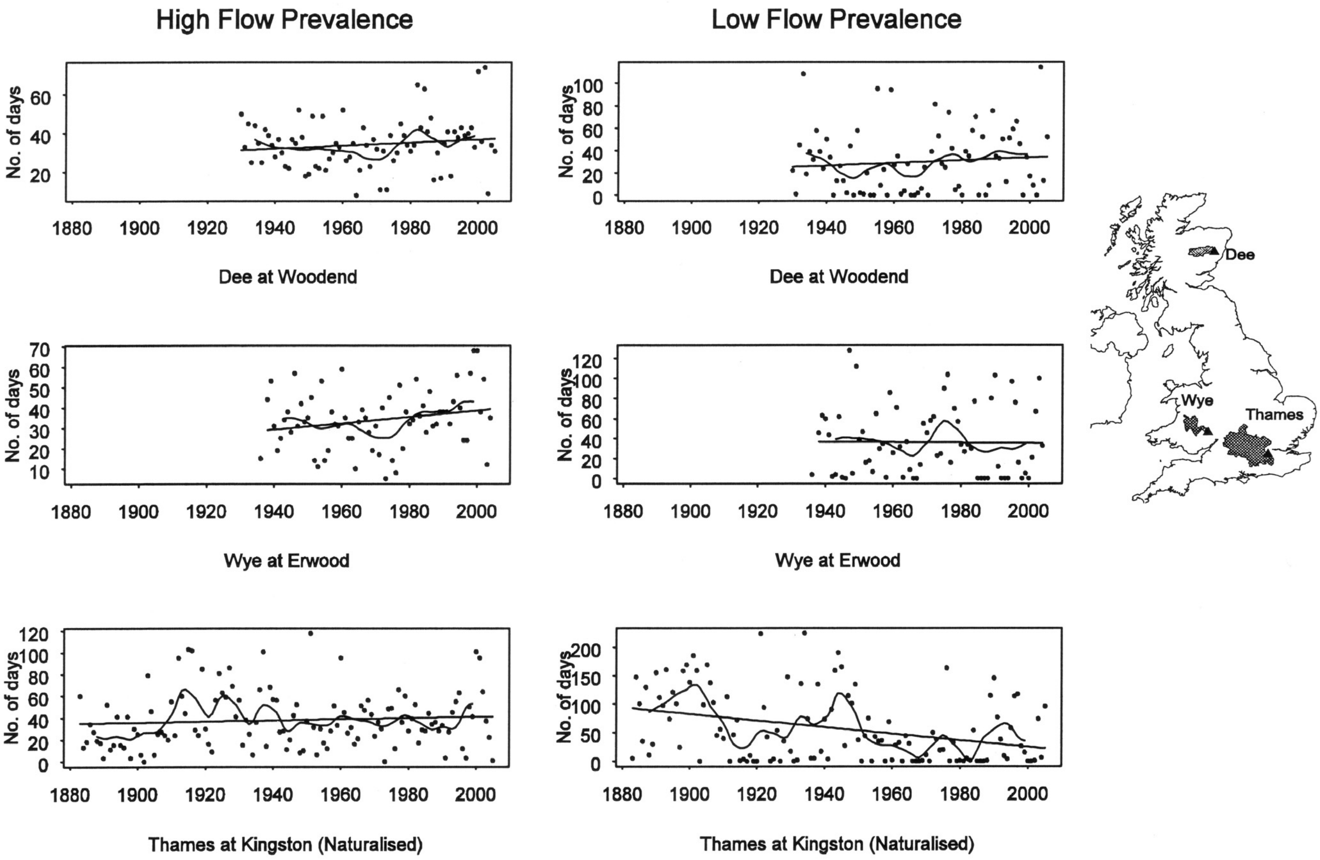

Fig. 4 Time series plots showing high flow (q10) and low flow (q90) prevalence trends for three long hydrometric records (LOESS smoothing curves are also shown), with a map showing the location of the three catchments.

fluctuations; a linear trend fitted from the early 1960s would yield a much steeper, significant positive trend.

For low flows, the Dee and the Wye show no evidence of significant long-term change. The negative low flow prevalence trend (reflecting a decrease in time spent at low flows) for the 121-year Thames record is partly influenced by a series of dry winters prior to 1910, but low flows during this period are known to be underestimated (Littlewood & Marsh, 1996). The long record does show clear evidence of clustering, which may lead to short-term trends implying decreasing low flows—there are a number of years with long periods of flows below q90 throughout the 1990s, in comparison with the 1980s where most years had no periods below q90.

Only three long records are presented in this short study—more work is required to appraise the quality of other long hydrometric records before a definitive characterization of long-term variability can be made.

CONCLUSIONS

This study has focused on a network of undisturbed catchments to discern natural variability from artificial impacts on flow regimes. This study has presented evidence for increasing high flows in maritime northern and western areas of the UK, complementing previous work on rainfall and runoff. Increasing high flow trends are consistent with some scenario-based climate model projections for the future although a predominantly positive NAOI over the latter half of the period suggests climatic variability is an important factor. There were few significant decreasing low flow trends in the benchmark catchments in lowland England, despite a clustering of droughts in the 1990s. The results presented here provide a baseline against which long-term historical variability and future change in river flow patterns can be quantified and interpreted.

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