The effect of record length on the analysis of river flow trends in Wales and central England

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Abstract The detection of trends in hydrological variables is directly affected by the length of time series available for analysis and is of key importance to the global FRIEND community. Long-term (≤50 years) seasonal gauging station records from Wales and the English Midlands are analysed for different time spans up to 2001 to demonstrate the effect of record length on linear trend analysis. Non-parametric Mann-Kendall trend methods are applied to time series of different flow quantiles, and for different seasons, thereby assessing trends across the streamflow spectrum. Key differences are quantified between trends of varying record lengths, but the dominant trend is for streamflow increases at high and low flows over time periods greater than 30 years. The implications for the FRIEND community are widespread and support the need to maintain gauging station networks and maximise instrumental records.

Key words high flows; hydrological data; Mann-Kendall; record length; seasonal river flow; streamflow; trend analysis; central England; Wales

INTRODUCTION

Defining temporal change in river discharge is a fundamental part of establishing hydrological variability, and crucially important for identifying climate–streamflow linkages, water resource planning, flood and drought management and for assessing geomorphological and hydro-ecological responses. Consequently, numerous studies of river flow time series have been carried out (e.g. Hisdal *et al.*, 2001; Burn & Hag Elnur, 2002; Robson, 2002; Lindstrom & Bergstrom, 2004), many using linear trend analysis (e.g. Lins & Slack, 1999; Zhang *et al.*, 2001).

Clearly, establishing the robustness of trend detection methods is vital to a sound definition of recent hydrological change. Ideally, long-term instrumental records are needed for secure establishment of trend, but few investigations have attempted to quantify the impact of different record lengths on hydrological trends. An exception is Hisdal *et al.*'s (2001) study of streamflow droughts across Europe that found substantial influences of study period on trend statistics. This paper, therefore, aims to highlight the effects of record length on river flow trends by analysing instrumental data at different decadal timescales drawn from Wales and central England, UK, over 35% of which are common to the FRIEND database. The paper focuses on seasonal breakdown analyses of the full discharge spectrum, from low to high flows. This is in contrast to many previous studies which tend to consider either floods or droughts for single sites or basins (but cf. Lins & Slack, 1999; Birsan *et al.*, 2005).

The work is part of a more comprehensive project on defining and explaining recent hydrological changes at larger spatial scales over the instrumental period in southern UK (Dixon *et al.*, 2005). The quantified impacts of record length on trend definitions will have significant implications for the analysis of spatial and temporal variability in hydrological systems which form the focus of much FRIEND community research.

STUDY AREA

This paper focuses upon the hydrologically dynamic, temperate Atlantic fringe of Wales and central England. For the purpose of this paper the area defined as Wales and the English Midlands covers a combined land area of around 46 800 km^2 of cool temperate basins at a range of scales (18–7500 km^2). The mountainous areas of Wales (maximum altitude 1085 m) and agricultural plains of the English Midlands fall within the study area. Urban coverage varies greatly and includes a number of major population centres, including Birmingham and Cardiff.

DATA SOURCES

Daily mean streamflow (DMF) records were selected for gauging stations from the National River Flow Archive (NRFA) at the Centre for Ecology and Hydrology (Wallingford) (http://www.nwl.ac.uk/ih/nrfa/). In most cases streamflow time series provided at Daily Mean (DMF) resolution were calculated from 15-minute recordings taken using a variety of gauging structures. A minimum record length of 25 years of continuous data was set, and where possible gauging stations were chosen that were free from large-scale local flow retention, notable gauging errors and changes in station location or gauging structure over the record length. The number of records included varies with the time series length under consideration, in that 56 stations were available for a 25 year period and eight stations for ≥50 years of record.

ANALYTICAL METHODS

Streamflow variables

As this paper is concerned with trends across the cumulative streamflow distributions, DMF records were used to calculate time series of flow quantiles at a seasonal resolution. The four standard UK Metl Office (http://www.met-office.gov.uk/) seasons were used: Dec/Jan/Feb; Mar/Apr/May; Jun/Jul/Aug; and Sep/Oct/Nov. This paper will mainly present regional trend patterns for the winter (Dec–Feb) streamflow spectrum.

The seasonal x-quantile $Q_x(i)$ of streamflow (q) was obtained for each year (i) as the value at which $\Pr(q \le Q) = x$ (e.g. Birsan *et al.*, 2005). Trend tests were applied to time series of $Q_x(i)$, where $i = 1, \ldots, t$ years. In order to investigate the full discharge spectrum, trends were analysed for 11 quantiles of the streamflow distribution, from the minimum (Q_{Min}) to the maximum (Q_{Max}) (e.g. Lins & Slack, 1999). The following quantiles of flow (as opposed to exceedence probabilities) were calculated: 10th ($Q_{0.1}$) low flow, 20th ($Q_{0.2}$), 30th ($Q_{0.3}$), 40th ($Q_{0.4}$), 50th ($Q_{0.5}$), 60th ($Q_{0.6}$), 70th ($Q_{0.7}$), 80th ($Q_{0.8}$) and 90th ($Q_{0.9}$) high flow percentiles. Trends in the mean streamflow (Q_{Mean}) over each relevant period were also calculated.

Record length

There are a number of problems associated with the analysis of trends in relatively short time series. Analysis was conducted for four time spans: t = 25 years (1977–2001) for 56 stations; t = 30 years (1972–2001) for 44 stations; t = 40 years (1962–2001) for 24 stations; and t = 50 years (1952–2001) for eight stations.

Trend analysis

Monotonic trends were analysed using the nonparametric Mann-Kendall test (Helsel & Hirsch, 1992) for each of the quantiles of the cumulative streamflow distribution (e.g. Lins & Slack, 1999). The test examines a given time series for linear increases or decreases with time rather than detecting episodic or abrupt events. The method is a rank based test and particularly useful for hydrological data sets as it is robust against outliers (see Kundzewicz & Robson, 2004). Being distribution-free, it is suited to the analysis of streamflow time series which tend to be non-normally distributed (e.g. Lettenmaier *et al.*, 1994; Zhang *et al.*, 2001; Birsan *et al.*, 2005).

Because trends are calculated for time series with yearly intervals, it is assumed that the impacts of serial correlation are likely to be low (Lins & Slack, 1999). Birsan *et al.* (2005) for example, found low serial correlation coefficients in similar data sets and concluded that the potentially more conservative method of pre-whitening time series that displayed autocorrelation had little overall difference in such cases.

Test statistic significance levels were determined using the flexible and robust method of bootstrap resampling, which makes relatively few assumptions about the independence and distribution of the data set (e.g. Kundzewicz & Robson, 2004). One thousand resamples were conducted for each test using the more flexible bootstrap (with replacement) method. This paper focuses on the trend results found to be significant at or above the 10% level ($\alpha \le 0.1$, two-tailed test).

The magnitude of trend (as change per year) has been calculated by applying Sen's (1968) nonparametric method to hydrological time series (e.g. Lettenmaier *et al.*, 1994; Burn & Hag Elnur, 2002; Kahya & Kalayci, 2004). In order to highlight any underlying longer-term variability in relation to different linear trends, example time series have been smoothed using the relatively robust locally-weighted regression smoothing method, LOESS (e.g. Robson, 2002).

RESULTS

Regional pattern

Figure 1 summarizes the effect of record length on statistically significant linear trends for all quantiles. It is important to note the different number of stations (n) available for analysis at the four different time periods. Figure 1 shows that, across all time periods and quantiles, the percentages of river flow records displaying statistically significant trends varies between 0 and 50%. Most significant changes are found at high and low flows. However, the impact of record length on trend patterns is immediately apparent. For example, the mixture of positive and negative trends present over the 25-year period (t = 25) is not found over the longer term. Winter maximum streamflow over the last 25 years (n = 56) show significant rising trends in 25% of time series and falling trends in around 18% (Fig. 1(a)). This streamflow decline, which represents 10 station records, is not found at $t \geq 30$ years. It is important to note that insufficient record lengths are not the cause of this isolated negative pattern as 9 out of the 10 stations in question are common to at least the t = 25 and t = 30 year analysis periods. At longer record lengths, the main pattern is an increasing trend for high and low flows.

The trend results of Fig. 1 are shown geographically in Fig. 2 for Q_{Max} flows, to allow identification of regional patterns. Analysis of the recent 25-year period (Fig. 2(a)) suggests a pattern of rising winter high flows in a band covering northern, central and southeast Wales, but falling high flows in lowland catchments to the east of the region. Although parts of the band of stations which display rising trends are still evident at $t \geq 30$ years, the pattern is patchy and many more stations display stationarity (Fig. 2(b) and (c)). The declining Q_{Max} flows in the Upper Trent

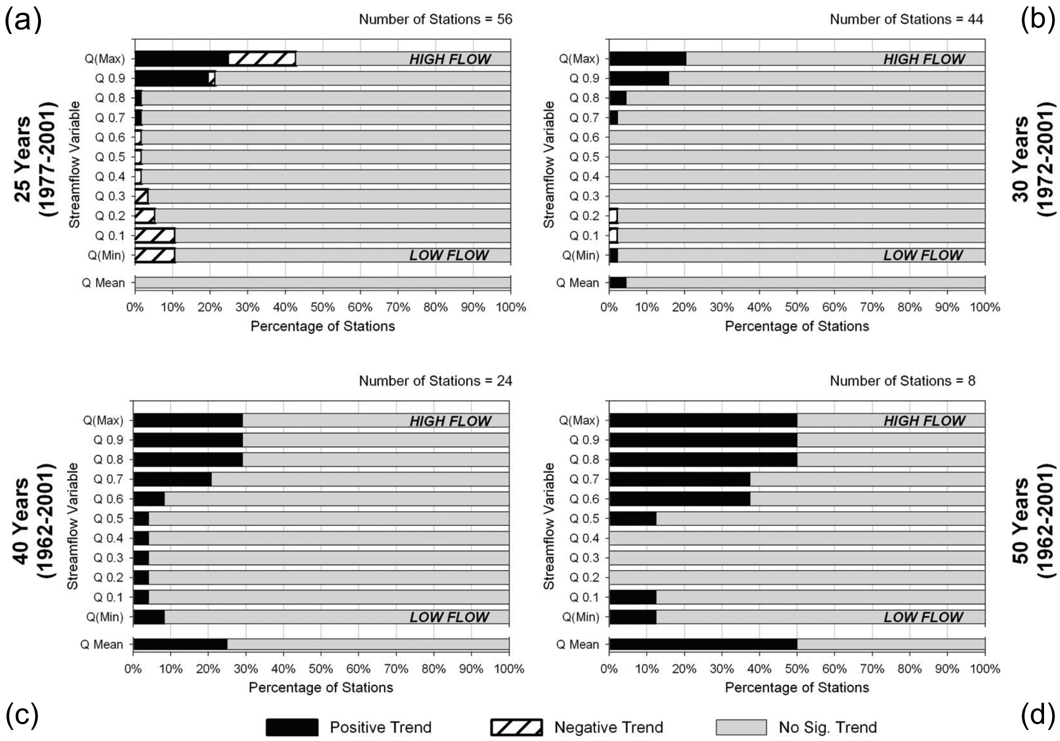

Fig. 1 Linear trends in winter (DJF) streamflow (significant at $\alpha \leq 0.1$) analysed for; (a) t = 25 years; (b) t = 30 years; (c) t = 40 years; (d) t = 50 years.

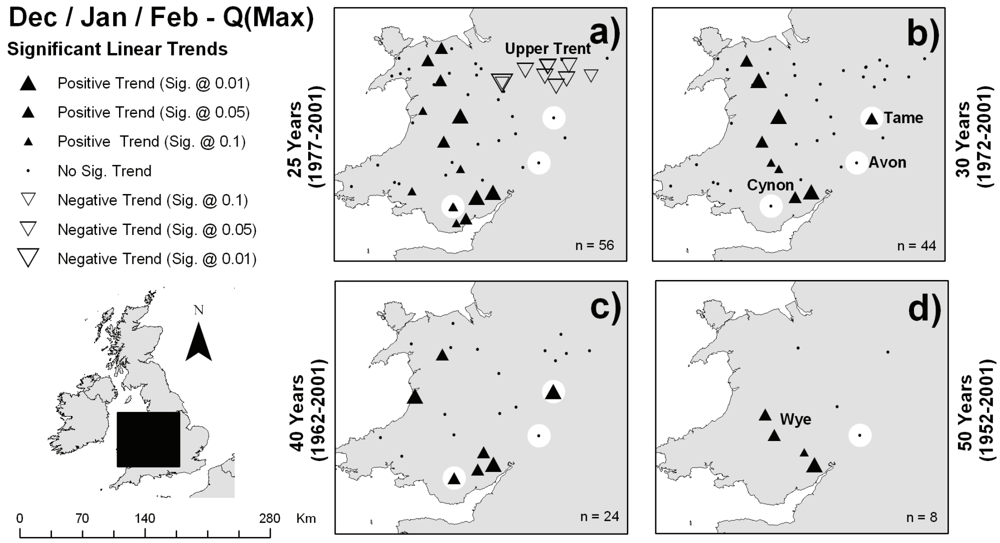

Fig. 2 Geographical variations in winter Q_{Max} streamflow trends (significant at $\alpha \leq 0.1$): (a) t = 25 years; (b) t = 30 years; (c) t = 40 years; (d) t = 50 years. Individual example gauging stations highlighted by white circles and labelled in 2(b).

show positive linear trends (Fig. 2(d)), the total number of records available is low (n = 8) and all of the statistically significant time series represent gaugings in the Wye catchment or tributaries.

Individual gauging station examples

The problems of varying analysis periods can be further demonstrated through the exploratory analysis of example time series for specific station quantiles for seasons (Figs 3, 4 and 5). The addition of LOESS smoothing and Sen's estimations of linear trend lines quantifies the record length issue. These example stations are located in Fig. 2(b).

For many time series the statistical significance of a trend can be directly affected by the analysis period chosen. Winter high flows on the River Tame (Fig. 2(b)), for example, display positive trends over 20, 30 and 40 years of the record (Fig. 3). However, the trend is only statistically significant (at $\alpha = 0.1$) for t = 30 and 40, suggesting that significant increases in winter maximum flows have not been continued into the post-1990 period.

A similar pattern emerges for summer $Q_{0.3}$ flows on the River Avon at Evesham (Fig. 2(b)), 50 km to the south of the River Tame: in this case fluctuations in the length of period considered cause a reversal of trends (Fig. 4). Statistically significant *increasing* trends are present over both the 50- and 60-year periods up to 2001, while for a medium length of record (t = 40 and 30 years) the time series displays a high degree of *stationarity*. However, analysis for 25 years (1977–2001) results in statistically significant *negative* trends.

The final example shows winter low flows (Q_{Min}) of the Cynon at Abercynon in South Wales (Fig. 2(b)). Here the long-term (t = 39 year) trend is *stationary*, but an analysis confined to the most recent 25 or 30 years shows a clear, significant flow *decline* (Fig. 5). This demonstrates the importance of analysing the fullest possible record lengths when identifying historical trends or making future projections.

DISCUSSION AND CONCLUSIONS

The recent increase in research and media interest in long term climatic and hydrological change has lead to speculation about trends of a number of hydro-meteorological variables. The present study has examined the trends in streamflow data of 56 stations in Wales and the English Midlands: 21 stations are common to the FRIEND network.

The detection of trends in hydrological data is a complex issue. This study has shown that the results of trend analysis are dependent on the chosen period: in particular, it can have significant

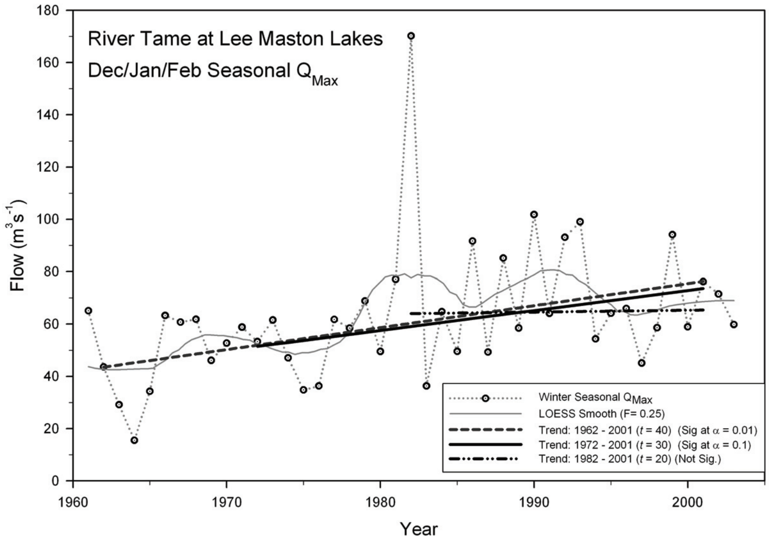

Fig. 3 Winter high flows (Q_{Max}) of the River Tame at Lee Marston Lakes. Mann-Kendall linear trends calculated over varying time periods.

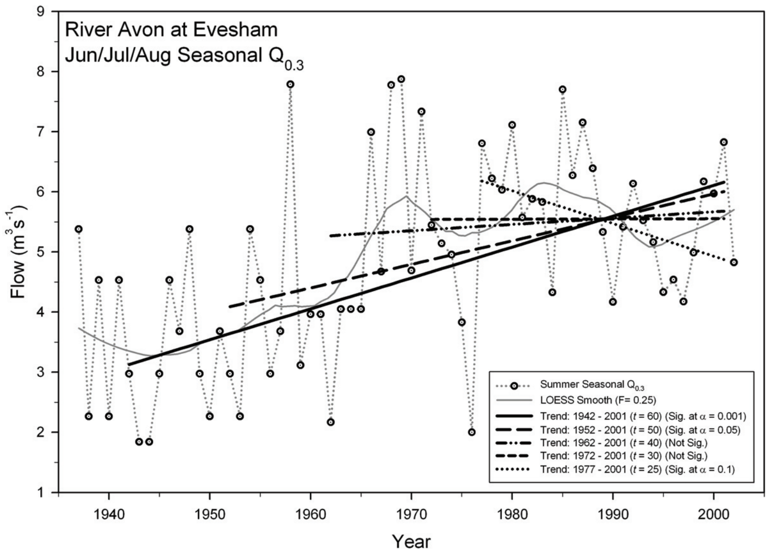

Fig. 4 Summer $Q_{0.3}$ flows of the Avon at Evesham. Mann-Kendall linear trends calculated over varying time periods.

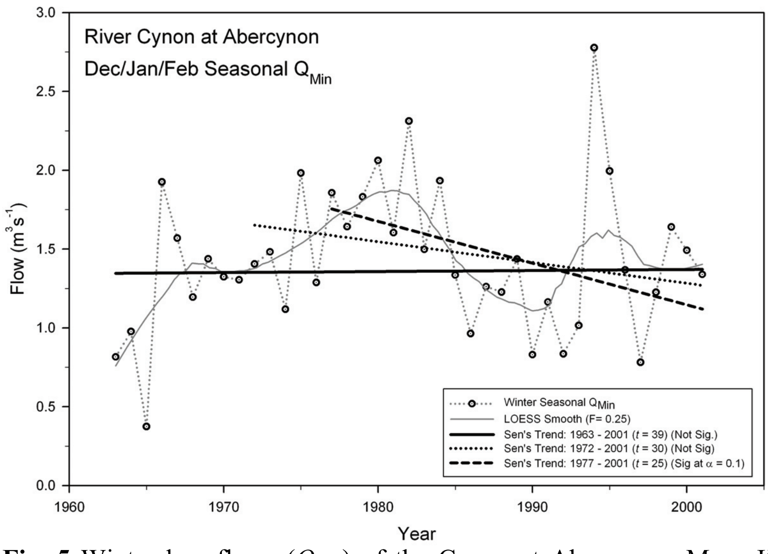

Fig. 5 Winter low flows (Q_{Min}) of the Cynon at Abercynon. Mann-Kendall linear trends calculated over varying time periods.

influence on both trend magnitude and the direction. The implications of analytical decisions on the interpretations of hydrological change are important and impact on planning and development in many fields including water resources, flood defence, hydro-ecology and climate-flow analysis. This study also confirms the importance of using the seasonal streamflow data in trend analysis, rather than simple annual means which can sometimes fail to reveal the full temporal complexity of flow trends.

Although, the trend analysis results here are found to vary across the flow quantiles used, the main feature is for streamflow increases at high and low flows for $t \geq 30$ years. The spatial pattern of trends is also affected by the chosen period of record. Some of the flow increases identified have recently been linked to increasing total rainfall receipts and the state of the North Atlantic Oscillation in the same area (Dixon *et al.*, 2005).

Future analysis will focus on any cyclic and step-change behaviour in the flow, rainfall and atmospheric circulation data, which has emerged for some stations (Dixon *et al.*, 2005). Other analysis could also incorporate a moving window method, using a shifting end date (e.g. Hisdal *et al.*, 2001; Lindstrom & Bergstrom, 2004).

The quantification presented here of the impact of record length in trend analysis demonstrates the need for careful analysis of hydrological time series and supports the use of the longest streamflow data sets available. The continued development of historical flow records, expansion of comprehensive river flow databases (such as the FRIEND European Water Archives: http://ewa.bafg.de/) and maintenance of high resolution river flow monitoring networks are central to further detection and understanding of hydrological change.

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