An assessment of runoff trends in undisturbed catchments in the Celtic regions of North West Europe

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Abstract This study presents results of trend tests applied to annual and seasonal runoff time series from a network of largely undisturbed catchments across the Celtic Region of northwest Europe (the British Isles and Brittany), with a view to discerning natural variability from artificial influences on flow regimes. Strong evidence of runoff increases over the last 40-years was found for Scotland and Ireland, and there were some significant increases in Wales, western England and Brittany, although the regional signals are less compelling in these areas. The findings have some parallels with climate change scenarios, although there were also strong associations with the North Atlantic Oscillation Index over this timescale; the influence of the NAO is likely to account for the spatial variability in the significance of trends which was observed over the region. The study provides a baseline against which to assess historical variability and future runoff trends in the Celtic region.

Key Words: Trend; runoff; river flow; climate change; natural catchments; monitoring networks; resampling; North Atlantic Oscillation

BACKGROUND

Regional Climate Model (RCM) scenarios for the UK forecast a future climate characterized by an enhanced seasonality, with wetter winters and warmer, drier summers (Hulme *et al.* 2002); the increases in winter rainfall are expected to be greatest in upland Celtic regions of the north and west, with a more pronounced gradient between these areas and lowland Britain. If realized, these changes would have severe implications for the management of hydrological risks and resources in the Celtic region - for Scotland. Werritty (2002) documents the scope of these seasonal changes on water utilization patterns and Black & Burns (2002) examine the increased flood risk associated with increased rainfall.

However, there is considerable uncertainty as to the nature and magnitude of the potential future impacts of climatic changes on river flows. Consequently, monitoring programmes have an important role to play in climate change research, in providing ground-truth for modeling approaches by detecting any emerging trends in hydrological data. The recent past has undoubtedly been characterized by a notable hydrological volatility, with recent variability in river flow records in the Celtic regions approaching the extreme ranges of recorded variability (Green *et al.* 1996). However, whilst trends in high flows and runoff have been identified for Scotland (Black, 1996) evidence for an underlying climatic-driven trend on flow regimes in most areas remains inconclusive, for both high flows (Robson *et al.* 1998) and low flows (Hisdal *et al.* 2001).

The Celtic areas of the UK share many climatic, geological and physiographic traits with the Republic of Ireland and Brittany. The Celtic region of maritime northwest Europe is characterized by outcroppings of resistant rocks, with minimal influence of groundwater, and climates are dominated by the paths of depressions which cross the north Atlantic (Rodda, 1996). It is likely that emerging river flow trends observed in the UK would have parallels with changes seen in the other Celtic regions on the north Atlantic seaboard of Europe, particularly if these trends are caused by underlying changes in westerly airflows. Hitherto, there appear to have been few studies directed towards trends in these areas, with the exception of the long records examined by Green *et al.* (1996) and the work of Kiely (1999) which identified trends in rainfall and streamflow records in Ireland.

Trend detection in many European countries is made problematic by the pervasive impact of direct anthropogenic impacts on flow regimes; in the predominantly upland Celtic regions, the influence of impoundments and hydropower developments are the commonest artificial influences. Such impacts serve to obscure natural, climate-driven signals. For this reason, a network of 'benchmark' catchments has been identified in the UK - establishing a capacity to discern natural signals from other, more direct anthropogenic impacts. The benchmark catchments were chosen on the basis of being free from significant artificial influences and have gauging stations with good hydrometric performance across the flow range, as discussed by Bradford & Marsh (2003).

STUDY OBJECTIVES

The aim of the present study is to use runoff data from the UK benchmark network, in association with runoff data from relatively natural catchments in Ireland and Brittany, to examine evidence for river flow trends and changes in seasonal runoff across the Celtic region of maritime northwest Europe, and characterizing any spatial variability in observed runoff trends. This work will establish a 'baseline' of recent trends across the Celtic region, within which to assess longer-term changes in hydrometric records and assist in the evaluation of climate change scenario formulations and the development of water policy initiatives.

DATA AND STUDY PERIODS

Data were collected for flow gauging stations from the benchmark network for Scotland, Wales, Northern Ireland and south west England (stations in Cornwall were complemented by other stations in the south west peninsula, which are comparable in terms of geology and rainfall).

Several gauges from the North West of England were also included as these have similar characteristics to the Celtic regions *per se*. All data were obtained from the National River Flow Archive at CEH Wallingford.

For the Republic of Ireland and Brittany, catchments were selected following liaison with local hydrometric staff and web-based metadata - selections could not be as well informed as the selection of the benchmark network, owing to the limited availability of metadata on artificial influences, although hydrograph inspection confirmed that the catchments displayed an essentially natural response. For all stations, time series of annual runoff were generated. For stations in the UK and Ireland, this was complemented by winter half year (October - March) and summer half year (April - September) seasonal series.

Previous studies have identified the inherent problems associated with the relatively short length of most hydrometric records and the sensitivity of trend tests to the study periods over which the statistical tests are applied (*e.g.* Robson *et al.* 1998). For this study, study periods reflecting a compromise between a reasonable spatial coverage over the Celtic region and record length were selected: a 35-year period, from 1969 - 2003 (60 stations) and 40-year period, from 1964 - 2003 (31 stations). For four stations in Ireland, no records were available until 1971/1972; these stations were included in the analysis to give some coverage in the north of the island.

TREND TESTS AND PERMUTATION METHODS

Linear regression was used to test for the presence of trend. Permutation tests were then used to asses significance of trends; unlike conventional tests, this approach has the advantage of not assuming an underlying distribution for the data. The permutation approach used here is described in detail in Davison & Hinkley (1997) and Kundzewicz & Robson (2000) describe its application for hydrological data. Briefly, the approach can be summarised as follows: a time series is randomly resampled (without replacement) S times - in the case of this study, $S = 1000$ - and the test statistic, T, is applied to each 'permutation' of the data. The T statistic for the original time series is located on the distribution of the T values from resampling to derive a p value; under the null hypothesis of no trend, any ordering of the data is equally as likely, hence, if the original test statistic is in the tails of the distribution, it is likely that the ordering of the data affects the test statistic and thus that trend is present.

The time series were tested for autocorrelation, which can increase the probability of detecting trends when none are present (Yue *et al.* 2002). There was no significant autocorrelation in the vast majority (97.5%) of time series, which was expected for the Celtic regions where baseflow contributions to river flow are generally modest, resulting in less persistence between years.

RESULTS

Table 1 shows the results of the trend tests for both standard periods and for the seasonal runoff data.

Table 1: Percentages of trends in various significance classes (according to p values, NS = not significant) for whole Celtic region, for annual runoff (two standard periods) and for seasonal runoff (1968 - 2003).

	Negative Trends (*p*)				Positive Trends (*p*)			
	NS	**>-0.05**	**>-0.01**	**->0.001**	**<0.001**	**<0.01**	**<0.05**	**NS**
Annual Runoff								
1968 - 2003	1.7	0	0	0	13.3	15.0	18.3	51.7
1963 - 2003	3.2	0	0	0	19.4	12.9	16.1	48.4
Seasonal Runoff (1968-2003)								
Winter (Oct-Mar)	2.2	0	0	0	20.0	15.6	13.3	48.9
Summer (Apr - Sep)	26.0	0	0	0	0	0	2.0	72.0

The results show that annual runoff has increased since the mid-1960s, with broad agreement between the 35-year and 40-year periods - around half the catchments recorded significant positive trends, and half recorded non-significant but increasing trends. In both cases only one catchment recorded a negative (non-significant) trend. The seasonal data (Table 1) demonstrate that the increasing trend in runoff is principally a result of high winter flows- 50% of winter time-series display significant positive trends. For the summer runoff, there were very few significant trends - of the non-significant trends there were 26% which were found to be decreasing.

Fig 1 shows the geographical distribution of trends across the Celtic region. Whilst it appears that runoff is increasing across the region, there are greater concentrations of statistically significant results in Scotland and Ireland. In Scotland, the positive runoff signal is strongest in the south west. The results agree with those of Black (1996), who observed positive runoff trends in Scottish catchments influenced by westerly airflows up to 1995, and Werrity (2002) who observed runoff increases in southern and central areas from 1970-1995. The present study reinforces and updates these observations, but we also report some significant trends in catchments with an eastern aspect (such as the Dee). In Ireland, significant trends were found along the western coast, and in northern areas. Kiely (1999) also found positive trends in four Irish streamflow records up to 1995, and in the same study identified increases in rainfall in long rainfall records in Ireland, observing that the strongest signals were for western areas, which is likely to account for the increasing runoff observed here.

In England and Wales, there were individual significant trends but the results are less spatially consistent than for Scotland or Ireland; some significant trends were observed in central and southern Wales, Cornwall and Cumbria, although trends were non-significant in other nearby catchments. Similarly, for Brittany there were also few significant trends except in the far west of peninsula.

DISCUSSION

The results of this study suggest there is strong evidence for increasing runoff in Scotland and Ireland over the last forty years. The signals are less compelling for England and Wales and Brittany, which show isolated cases of significant trends.

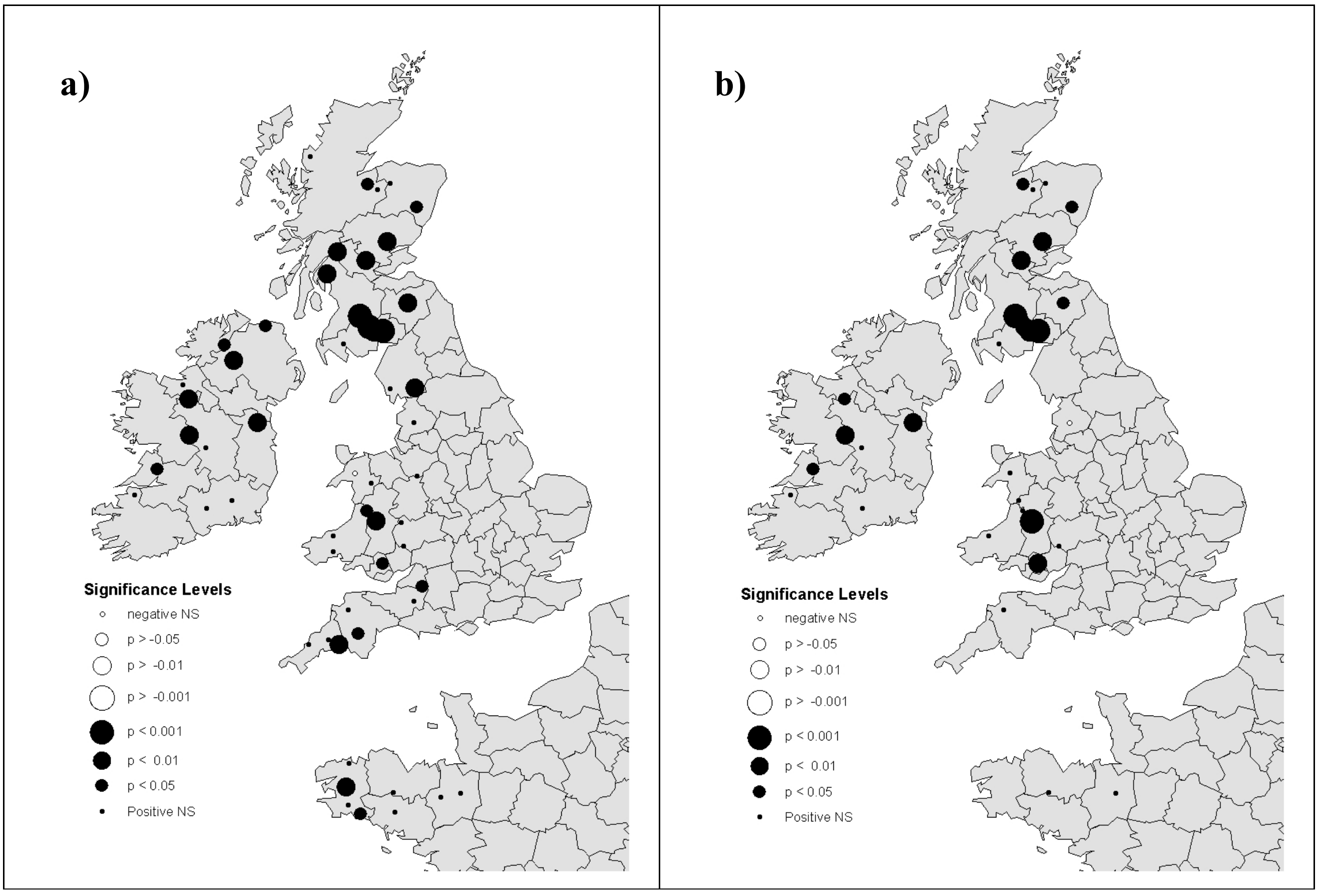

Fig. 1 Results of significance tests for catchments across Celtic region. Proportional symbols show significance level (*p* values) of tests according to key. a) 1969 - 2003 period; b) 1964 - 2003 period.

However, the prevalence of positive, albeit non-significant trends suggests a tendency towards modest increases in runoff in these western, maritime areas. In the context of Great Britain as a whole, the increases in runoff in western areas agrees with other studies which have identified contrasts in runoff variability between the upland Celtic regions of the western UK and lowland areas to the east (Green *et al.* 1996), and studies of rainfall trends which have identified an enhanced NW/SE rainfall gradient across Great Britain since the 1960s, with stronger positive trends in rainfall in northern and western areas (Mayes, 1996; Jones & Conway, 1997; Osborn, 2000). The broad contrast between west and east across the UK is reflected to a lesser extent in the contrast between western and eastern areas of Scotland observed in the present study, which is much less pronounced but probably a consequence of similar mechanisms.

Observed rainfall increases in western areas and enhanced seasonality has been attributed to an increased predominance of westerly airflows (Mayes, 1996; Wilby, *et al*. 1997), which in turn reflect an upward trend in the North Atlantic Oscillation Index (NAOI). The NAOI has increased overall since the early 1960s and was strongly positive from the early 1980s (Wilby *et al.* 1997) until very recently. To examine associations between the NAO and runoff, winter runoff time series for benchmark catchments in the British Isles were correlated with the winter NAOI over the 1963 - 2002 period. Correlation coefficients were highest in Scotland (average r=0.47) most notably in catchments exposed to westerly airflows, such as the Nith (r=0.63) and Tay (r=0.67). Catchments with an easterly aspect were less strongly correlated (*e.g.* Tweed r=0.38, Dee r=0.22). Similar East/West contrasts were observed in Ireland. Correlations were weaker in Wales (average r=0.33) and in the SW peninsula - the two catchments with sufficient record length had correlations of r=0.29 (Torridge) and a negative correlation of r=-0.17 for the Otter. These results suggest a north-south contrast in the strength of relationships with the NAO in Celtic areas, and support the work of Shorthouse & Arnell (1997) who found strong correlations between NAOI and regional flow indices in northern and western areas of the UK, and found weaker relationships in the SW peninsula and Brittany. Fig 2 portrays the contrast between the Nith, in western Scotland, and the Torridge, SW England, in comparison with the NAOI. The north/south contrast reflects the influence of the NAO on atmospheric circulation patterns and storm tracks, and is part of a European-wide contrast between northern Europe/Scandinavia and the Mediterranean (Shorthouse & Arnell, 1997; Marshall *et al.* 2002).

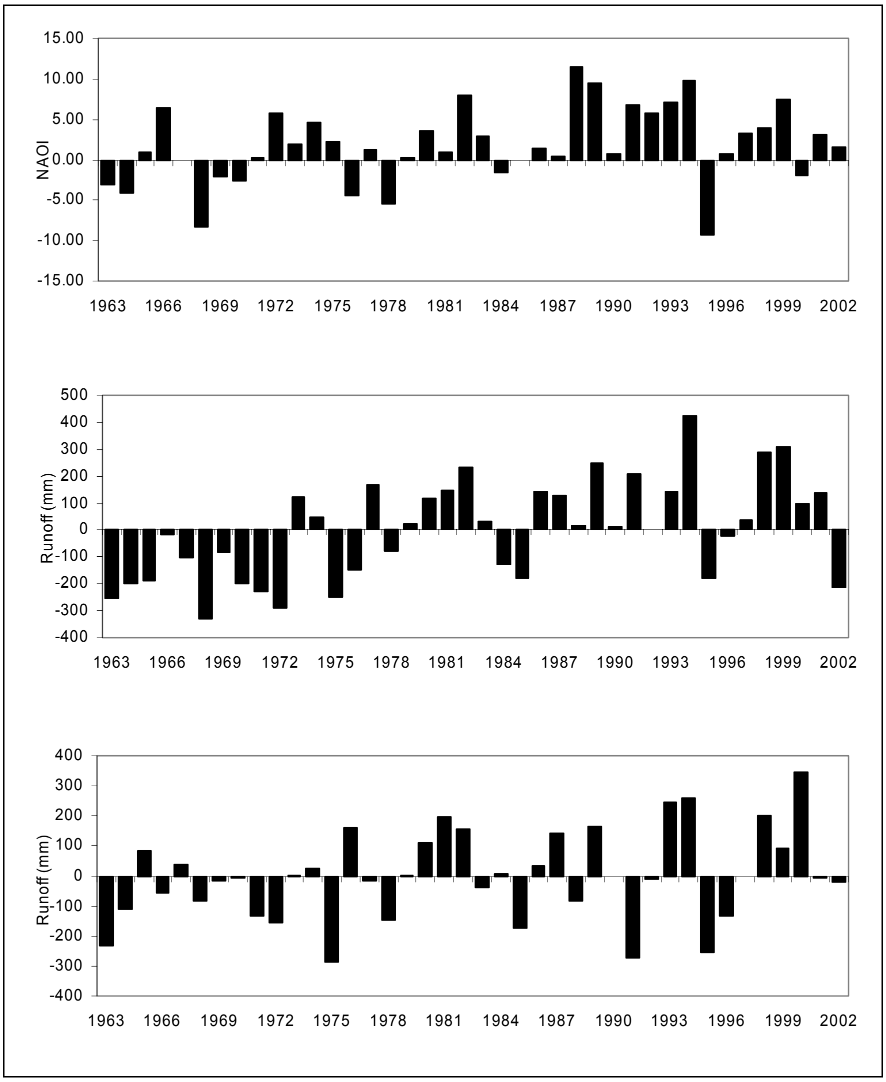

Fig. 2 Time series plots of winter NAOI and winter runoff for selected catchments, expressed as deviation from 1963 - 2002 mean. Top: Winter North Atlantic Oscillation Index (NAOI); Centre: Winter Runoff from River Nith, Scotland; Bottom: winter runoff from River Torridge, SW England.

CONCLUSION

A distinctive feature of this study is its emphasis on natural catchments, in order to discern natural variability from the net impact of artificial influences. The study has thus demonstrated that there have been significant increases in runoff over the last forty years in Scotland and Ireland, and a general tendency towards increasing runoff in Celtic areas. These findings have some parallels with climate change scenarios, although no decline in summer runoff was detected and, importantly, the limited length of records is an obstacle to attributing trends to a climatic origin. Moreover, the increase over the timeframe is associated with an upward trend the NAOI, which complicates the question as to whether these patterns are manifestations of climate variability or long-term change - previous authors have commented on the complexities underlying interactions between teleconnections and anthropogenic warming (Wilby *et al.* 1997). Interestingly, the correlations with the NAO do suggest the east-west and north-south contrasts observed in runoff trend in the Celtic region (and surrounding lowland areas) is a result of the influence of westerly airflows and associated circulation patterns associated with the NAO.

The positive trends in runoff for Scotland and Ireland indicate a significantly more favourable water resources outlook than was perceived in the 1960s - 1970s. This is reinforced by the lack of any significant trends in summer runoff. This short study has not addressed the magnitude of these trends - further work is required to investigate the magnitude of changes in detail and to consider the implications of such change. However, the results provide a baseline against which to assess recent trends in a broader historical context, and to assess future changes in runoff. This should be undertaken utilizing dedicated networks of natural catchments such as the benchmark network employed in this study.

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