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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 catchments across the Celtic regions of the northwest European Atlantic margin, namely northern and western areas of the British Isles and Brittany. The aim is to provide an overview of natural, climate-driven runoff trends across the Celtic region by focusing on catchments undisturbed by artificial influences (e.g. impoundments and hydropower development) on flow regimes. Strong evidence of increasing runoff over the 40 years from 1964 to 2003 was found for Scotland and Ireland, and there were some significant increases in Wales, western England and Brittany. The regional signals are less compelling in these areas, but the predominance of positive trends observed in this study suggests a tendency towards a region-wide increase. Annual runoff trends were associated with increases in winter runoff; there was no evidence for any decline in summer runoff over the period. The findings have some parallels with climate change scenarios, although there were also strong associations with the North Atlantic Oscillation Index over the timescale used in this study. The study provides a baseline against which to assess historical variability and future runoff trends in the Celtic region.

Key words climate change; monitoring networks; natural catchments; North Atlantic Oscillation; resampling; river flow; runoff; trend

BACKGROUND

Regional Climate Model (RCM) projections for the UK forecast a future climate characterized by an enhanced seasonality, with wetter winters and warmer, drier summers (Hulme *et al.*, 2002). If realized, these changes would have major implications for the management of hydrological risks and resources in Celtic regions of the UK; for example, for Scotland, Werrity (2002) documents potential impacts of increased rainfall on flood regimes, and the effect of decreased summer rainfall and increased temperatures on water utilization patterns and aquatic ecosystems.

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 modelling 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 recent increases 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 in Ireland and Brittany 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, so 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. This overview of the Celtic region as a whole will enable an assessment of regional consistency in runoff patterns, and will provide a "baseline" of recent trends across region, against which to assess longer-term changes in hydrometric records and, ultimately, to assist in the evaluation of climate change scenario formulations and the development of water policy initiatives.

DATA AND STUDY PERIODS

Data was collected for flow gauging stations from the benchmark network for Scotland, Wales, Northern Ireland and southwest England (stations in Cornwall were complemented by other stations in the southwest peninsula, which are comparable in terms of geology and rainfall). Several gauges from the upland northwest 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 appraisal of 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 paper, 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 to 2003 (60 stations) and a 40-year period, from 1964 to 2003 (31 stations). For four stations in Ireland and Northern 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 assess the 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 summarized 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.

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.

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

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 was only one significant trend; of the non-significant trends, a majority were positive, with 26% which were found to be decreasing.

Figure 1 shows the geographical distribution of annual runoff trends across the Celtic region. Whilst it appears that runoff is increasing across the region, there are

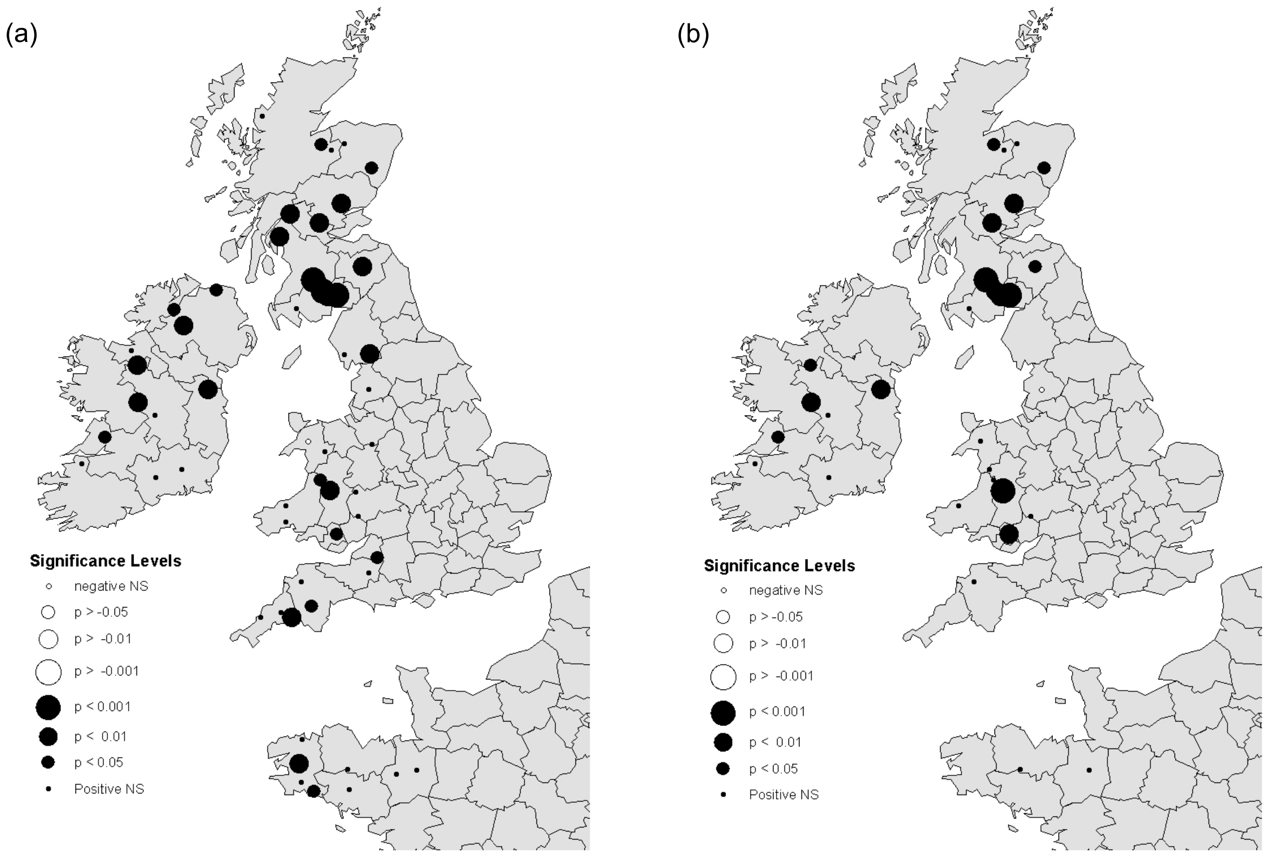

Fig. 1 Results of significance tests for catchments across Celtic region. Proportional symbols show significance level (p values) of tests according to key. (a) 1969–2003 period; (b) 1964–2003 period.

greater concentrations of statistically significant results in Scotland and Ireland. In Scotland, the positive runoff signal is strongest in the southwest. The results agree with those of Black (1996), who observed increases in runoff in Scottish catchments influenced by westerly airflows up to 1995, and Werrity (2002) who observed runoff increases in southern and central areas from 1970 to 1995. The present study reinforces and updates these observations, but there were also significant trends in some catchments with an eastern aspect (such as the Dee in northeast Scotland). In Ireland, significant trends were generally found in northern and western 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 trends were in western areas.

In England and Wales, runoff has increased in almost all catchments, but whilst there were individual significant trends the results are less spatially consistent than for Scotland or Ireland; some significant trends were observed in central and southern Wales and southwest England but the regional signals are less compelling owing to the low number of significant trends. For Brittany there were no significant trends except in the far west of the peninsula.

DISCUSSION

The results of this study show some variation in runoff trends across the Celtic region, with stronger evidence for increasing runoff in Scotland and Ireland. However, the prevalence of positive, albeit non-significant trends suggests a tendency towards modest increases in runoff in all western, maritime areas of the North Atlantic Celtic region.

In the context of Great Britain as a whole, the increase 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 strong positive trends in rainfall in northern and western areas (Mayes, 1996; Jones & Conway, 1997; Osborn, 2000).

Increases in rainfall in western areas have been attributed to a greater 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 the late 1990s. 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 southwest peninsula where 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 southwest peninsula and Brittany. Figure 2 portrays runoff anomalies for the River Nith, in southwest Scotland, and the Torridge, southwest 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).

The association of annual runoff trends over the timeframe with an upward trend in the NAOI complicates the question as to whether these patterns are manifestations of NAO-induced multi-decadal variability or long-term climatic change. Whilst the NAO is an influential factor, the NAO itself is affected by anthropogenic warming—

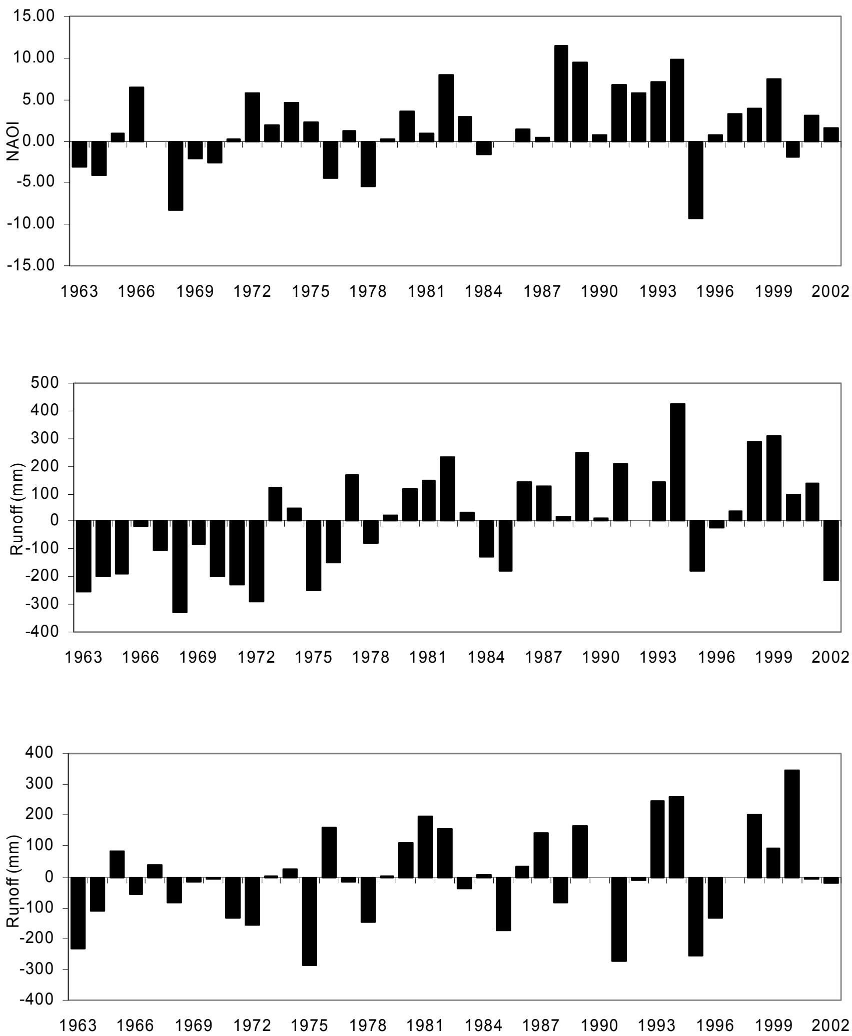

Fig. 2 Time series plots of winter NAOI and winter runoff for selected catchments, expressed as deviation from 1963–2002 mean. Top: winter North Atlantic Oscillation Index (NAOI); Centre: winter runoff from River Nith, Scotland; Bottom: winter runoff from River Torridge, southwest England.

previous authors have commented on the complexities underlying interactions between teleconnections and anthropogenic warming (Wilby *et al.*, 1997).

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 40 years in Scotland and Ireland. Significant results were less prevalent in England, Wales and Brittany, but a general tendency towards increasing runoff in Celtic areas is evident from the predominance of positive trends.

These findings have some parallels with climate change scenarios which project increases in winter rainfall in the Celtic region. Importantly, however, no decline in summer runoff was detected. The limited length of the records used in this study is an obstacle to attributing trends to a climatic origin, and the association of increasing runoff with changes in westerly airflows over the study period suggests that multi-decadal variability associated with the NAO may be an influential factor.

This short study has not addressed the magnitude of these trends; further work is required to investigate the magnitude of observed changes in detail and to consider the implications of such change. Most importantly, there is a need to compare these 40-year trends with longer hydrometric records from the UK, which are limited in number and reliability, but crucial to a long-term understanding of change.

The results of this study 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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