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# Climate-driven trends in mean and high flows from a network of reference stations in Ireland

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**Abstract** This paper introduces a reference hydrometric network for Ireland and examines the derived flow archive for evidence of climate-driven trends in mean and high river flows. The Mann-Kendall and Theil-Sen tests are applied to eight hydroclimatic indicators for fixed and variable (start and end date) records. Spatial coherence and similarities of trends with rainfall suggest they are climate driven; however, large temporal variability makes it difficult to discern widely-expected anthropogenic climate change signals at this point in time. Trends in summer mean flows and recent winter means are at odds with those expected for anthropogenic climate change. High-flow indicators show strong and persistent positive trends, are less affected by variability and may provide earlier climate change signals than mean flows. The results highlight the caution required in using fixed periods of record for trend analysis, recognizing the trade-off between record length, network density and geographic coverage.

**Key words** climate change; detection; high flows; Ireland; Mann-Kendall; mean flows; persistence; reference network; Theil-Sen; trend

### Tendances induites par le climat dans les séries de débits moyens et élevés à partir d'un réseau de stations de référence en Irlande

**Résumé** Cet article présente un réseau hydrométrique de référence pour l'Irlande et étudie les débits tirés des données d'archives pour mettre en évidence les tendances induites par le climat dans les séries de débits moyens et élevés. Les tests de Mann-Kendall et Theil-Sen ont été appliqués à huit indicateurs hydroclimatiques pour des enregistrements dont les dates de début et de fin étaient fixes ou variables. La cohérence spatiale et la similitude des tendances avec celles des précipitations suggèrent que la variabilité de ces indicateurs est induite par le climat, bien qu'une grande variabilité temporelle rende difficile à l'heure actuelle la mise en évidence très attendue de signaux de changements climatiques d'origine anthropique. Les tendances des débits moyens d'été et des débits moyens d'hiver récents sont en contradiction avec celles attendues du fait d'un changement climatique d'origine anthropique. Les indicateurs de débits de crue montrent des tendances positives fortes et persistantes qui présentent moins de variabilité et peuvent fournir des signaux du changement climatique plus précoces que ceux des débits moyens. Les résultats montrent qu'il faut utiliser avec précaution les périodes d'enregistrement fixes pour l'analyse des tendances, et reconnaissent le compromis entre durée des enregistrements, densité du réseau et couverture géographique.

**Mots clefs** changement climatique; détection; débits élevés; Irlande; Mann-Kendall; débits moyens; persistance; réseau de référence; Theil-Sen; tendance

## 1 INTRODUCTION

There is evidence that radiative forcing by anthropogenic greenhouse gases has affected the global water cycle over the last 50 years (Gedney *et al*. 2006, Huntington 2006, IPCC 2007, Barnett *et al*. 2008). This includes increasing annual runoff in some high-latitude regions (Milly *et al*. 2005), changes to the intensity of heavy precipitation (Groisman *et al*. 2005), and increased frequencies of great floods (Milly *et al*. 2005) and droughts (Dai *et al*. 2004). However, detection of climate-driven trends at regional scales is problematic due to the weak climate change signal relative to the large inter-annual variability of hydroclimatic metrics (Wilby *et al*. 2008). In addition, other human pressures within river catchments—such as land-use change, water storage, abstraction, diversion and urbanization—confound trend detection and attribution (Kundzewicz and Robson 2004, Radziejewski and Kundezewicz 2004, Svensson *et al.* 2005, Wilby *et al.* 2008, Fowler and Wilby 2010). Discussions about how to formally detect and attribute trends in flood series are not yet fully resolved, but it is recognized that studies need to be more hypothesis driven (Merz *et al.* 2012).

Ensembles of global climate models, greenhouse gas emission scenarios, downscaling approaches and multiple rainfall–runoff models for Ireland project increased flows in winter and lower flows in summer, modulated by catchment properties (Charlton *et al*. 2006, Steele-Dunne *et al*. 2008, Bastola *et al*. 2011a). Although uncertainties are large, studies suggest that catchment-specific impacts may pose challenges to water management and effective defence from extreme events (Bastola *et al*. 2011b, 2011c, Hall and Murphy 2011, Murphy *et al.* 2011). Consequently, early detection of changing water resources and extreme events due to climate change can help warn of negative environmental and societal impacts at individual catchment scales (Ziegler *et al*. 2005), or accelerate adaptation responses to emergent threats and opportunities.

Considerable changes have been observed in hydroclimatic variables in Ireland, although the majority of research has focused on precipitation. An analysis of trends in precipitation records from 1941 to 1999 found that rainfall totals, rain days and wet days have significant (10% level) increases at many stations in March and decreases in July, August and September (Sheridan 2001). Notable increases in the frequency of March rainfall and wet days have also been reported for eight synoptic stations (McElwain and Sweeney 2003). Seasonal analysis from 1960 to 2000 shows winter increases in the northwest and decreases in the southeast of Ireland; however, these monotonic changes were not statistically significant (McElwain and Sweeney 2007). Additionally, research has highlighted that extreme rainfall events have become more common in Ireland since 1975 linked to a change in the North Atlantic Oscillation Index (NAOI) around that time (Kiely 1999, Leahy and Kiely 2011).

Few studies have assessed Irish river flow data for evidence of long-term climate-driven changes. The mid 1970s change point detected in precipitation was also identified in four river flow records and correlated with the NAOI (Kiely 1999). It was shown that river flows have been increasing since the change point. Hannaford *et al*. (2005) found significant (5% level) linear trends along the western and northern coast of Ireland from 1968 to 2003 in winter and annual mean flows, but no significant trends in summer. Apart from these studies, analyses of national-scale trends have been hindered by a lack of metadata on river flow gauges to inform station selection. Given Ireland's location on the Atlantic fringe of Europe, this marks an important knowledge gap on regional hydrological trends which this paper addresses.

Given the large uncertainties attached to climate change impact studies, there is a need to more fully understand how climate change signals are manifested, or not, in observations, and whether agreements/disparities with model-based predictions can be reconciled and verified (Hannaford and Marsh 2006, Wilby *et al*. 2008). Over the past 15 years, a growing number of countries have invested in Reference Hydrometric Networks (RHNs) (Whitfield *et al*. 2012), in order to collect data that are minimally affected by confounding human influences (Stahl *et al*. 2010). RHNs provide a more reliable basis for detecting climate variability and change, and are increasingly employed in trend analyses (e.g. Lins and Slack 1999, Douglas *et al*. 2000, Zhang *et al*. 2001, Adamowski and Bocci 2002, Burn and Hag Elnur 2002, Yue and Wang 2002, Hannaford and Marsh 2006, 2008, Hannaford and Buys, 2012). In addition, RHNs facilitate more focused and strategic investment in monitoring, increased understanding of hydrological change and a heightened awareness of the importance of long river flow series for contextualizing trends from recent decades.

Nationally, there has been a rich history of hydrological monitoring that has resulted in a network of active hydrometric gauging stations with good geographical coverage, in some cases dating back to the 1940s. Historic priorities for hydrometric network design did not include climate change; rather, factors such as monitoring of arterial drainage works for agricultural land improvement and flood risk management, electricity generation, infrastructure development, flood warning, and management of extreme events have been the drivers of network expansion. There is therefore, a need to capitalize on the existing network to identify reference river flow gauges representing good quality stations with good rating curves, non-impacted flow regimes and long records, indicative of a range of physical settings that can be used for monitoring climate change across the flow regime.

In this paper, the objectives are twofold: firstly to introduce a reference hydrometric network for Ireland and secondly to examine the flow archive for evidence of climate-driven changes in mean and high river flows. The paper is organized as follows; Section 2 details the identification of an Irish Reference Network, Section 3 provides an overview of the study design and methods employed, and Section 4 presents trend analysis results for a fixed period, 1976–2009. Limitations of fixed-period-of-record approaches to trend analyses are highlighted, in particular the sensitivity of results to variability and outliers in the record, while the persistence and robustness of trends over time are explored. Section 5 presents a discussion of results, and identifies consistencies and inconsistencies with hypothesized drivers of change, before the key findings are distilled.

## 2 IDENTIFICATION OF THE IRISH REFERENCE NETWORK (IRN)

Criteria for the development of reference networks include the degree of basin development, the absence of river regulation, record length, station longevity and data accuracy (Pilon 2000). However, in realizing the full potential of existing hydrometric networks, compromises are often necessary for inclusion of representative catchment types and adequate spatial coverage. What constitutes "near-natural" conditions is very context dependent (Whitfield *et al*. 2012). Stahl *et al*. (2010) highlight that, in Europe, population density and human intervention with the natural landscape mean that truly natural catchments are hard to find. Some degree of disturbance must, therefore, be tolerated. For example, UK Benchmark Network catchments are considered as "near natural" where the net impact of abstractions and discharges are within 10% of the natural flow at, or in excess of Q95 (flow exceeded 95% of the time) (Bradford and Marsh 2003).

Similarly, the average record length of reference networks depends on the legacy and foresight of historical investments in monitoring. Decadal and inter-decadal climate variability affects the direction and magnitude of trends and, hence, it is important for reference networks to include time series of at least 50 years in length to distinguish short-term variability from anthropogenic change (Kundzewicz and Robson 2004). When selecting stations for inclusion in reference networks, a flexible approach is needed that balances stringency of criteria with the need for good geographical and temporal representativeness.

Individual stations for Ireland were subject to a number of criteria for inclusion based on best international RHN standards, most notably the UK Benchmark Network. Key criteria for Ireland include:

- good and consistent hydrometric data quality (particularly at extreme flow ranges), as determined by hydraulic conditions at each site (stable control and accurate rating curves);
- near natural flow regime—zero or stable water abstractions (impact less than 10% of flow at or in excess of Q95);
- long record length (minimum 25 years);
- limited land-use influence ($\leq$2.5% of catchment area developed); stations subject to arterial drainage were excluded where possible, otherwise post-drainage records were used if spatial coverage was lacking; and
- stations must be representative of Irish hydrological conditions and climatic regions with good geographical coverage, ensuring that stations from each of the eight Water Framework Directive (WFD) River Basin Districts (RBDs) are included.

In some circumstances, it was necessary for rules to be relaxed in order to capitalize on the existing network. For example, stations that have good hydrometric quality across the full flow regime are difficult to obtain (Hannaford and Marsh 2008), particularly in terms of quality ratings at high and low flow extremes. Therefore, some stations were excluded from the analysis of certain indicators. For instance, if a station showed good hydrometric performance for mean and low flow conditions, but lower quality at high flows, the record was included in the network but omitted from analysis of trends in high flows.

Avoidance of arterial drainage was particularly challenging given such widespread installation to improve agricultural land drainage and reduce flood risk. This has resulted in the deepening and widening of river channels resulting in changes in catchment response (Bhattarai and O'Connor 2004). For Irish conditions, Lynn (1981) notes an acceleration of catchment response to rainfall, with increased intensity of flood peaks and more rapid recessions post drainage. This would clearly confound detection and attribution of trends. Where a station was found to be drained, the post-drainage record was included for consideration and close attention paid to the comparison of trends from other non-drained stations to check for consistency. Only where there were no obvious inconsistencies with trends identified for non-drained stations were these stations included in the IRN. While attention was paid to ensuring homogeneity of records, a lack of metadata on land-use change meant that such influences cannot be entirely ruled out. Similar challenges have been noted by Hannaford and Marsh (2008).

Stations from Northern Ireland that are part of the UK Benchmark Network (Hannaford and Marsh 2006) were also included in the analysis to improve geographical coverage. The selection of stations for the IRN was undertaken in consultation with the principal hydrometric agencies, including the Environmental Protection Agency (EPA), the Office of Public Works (OPW) in Ireland, the Rivers Agency of Northern Ireland, and the National River Flow Archive (NFRA) at the Centre of Ecology and Hydrology (CEH). Thirty-five stations were identified for inclusion in the IRN plus a further eight from the UK Benchmark Network. For the IRN stations the average record length is 40 years with a minimum of 28 and the longest 63 years. Catchment areas range between 65 and 2460 km$^2$ with an average of 788 km$^2$. Table 1 provides details of all the stations selected for the IRN, including the UK Benchmark stations, which are also included in the analysis of the IRN conducted below.

## 3 DATA AND METHODS

The remainder of the paper presents the analysis of trends using the IRN records. While many indicators have been extracted, for ease of presentation and a lack of drought conditions in recent years in Ireland, the present analysis focuses on eight indicators reflecting changes in mean and high river flow conditions:

– Annual mean flow (ANmean)
– Seasonal mean flows (WImean, SPmean, SUmean, AUmean)
– Instantaneous annual maximum flow (IAMAX)
– Annual maximum 10-day flow (MAX10)
– Annual maximum 30-day flow (MAX30)

All indicators were calculated in cumecs (m$^3$ s$^{-1}$). Annual and seasonal means were extracted from daily mean flows. Seasons were defined as winter (DJF—December extracted from previous year), spring (MAM), summer (JJA) and autumn (SON). High-flow indicators were extracted from water years (1 October to 30 September) to limit the chance of dependence between high-flow events. IAMAX was derived from instantaneous 15-minute flows which were only available for stations maintained by the OPW and stations in Northern Ireland, so fewer stations are analysed for this indicator. Annual and seasonal precipitation totals for meteorological stations were also analysed for comparison with flows to determine the extent of covariance. Precipitation data were obtained from the Irish meteorological service (Met Éireann).

### 3.1 Missing data

Accuracy of individual indicators and trends extracted from flow records can be compromised by missing data. The majority of stations in the IRN have some degree of missing data (average 4.7%). In such situations Marsh (2002) highlights that inclusion of auditable and suitably flagged estimates of flow can increase the overall utility of the time series compared to leaving gaps. Consideration was given to different infilling techniques (Harvey *et al.* 2012), particularly the identification of donor stations where neighbouring stations were identified to develop regressions with target stations for infilling. However, in many instances the identification of donor stations that could fully account for missing data was found to be problematic, especially for long record stations in the network.

For consistency, missing data were in-filled using HYSIM (Manley 2006), a lumped conceptual rainfall–runoff model that has been previously applied in Ireland (Charlton *et al*. 2006, Murphy *et al.* 2006, Hall and Murphy 2012). The model was calibrated and verified for each catchment in the IRN with inputs of catchment precipitation and potential evapotranspiration. Modelling was conducted on a daily time step, hence infilling was not conducted for IAMAX. In all cases, in-filled data were visually inspected to ensure coherence with observations for periods before and after gaps. To further increase confidence, trend analysis was conducted for both incomplete and in-filled series for all stations in the network. The direction, magnitude and significance of trends were almost identical after infilling compared with unfilled test cases. With the exception of

**Table 1** Stations included in the Irish Reference Network (with UK benchmark stations for NI at bottom).

| Station | Station name | River name | RBD | Org | Easting | Northing | Area (km$^2$) | Length (year) |
|---|---|---|---|---|---|---|---|---|
| 6013 | Charleville Weir | Dee | NB | OPW | 304411 | 290763 | 309 | 34 |
| 6014 | Tallanstown Weir | Glyde | NB | OPW | 295298 | 297888 | 270 | 34 |
| 7009 | Navan Weir | Boyne | E | OPW | 287905 | 266761 | 1684 | 33 |
| 7012 | Slane Castle | Boyne | E | OPW | 294983 | 273962 | 2460 | 28 |
| 12001 | Scarawalsh | Scarawalsh | SE | OPW | 298380 | 145014 | 1031 | 54 |
| 14007 | Derrybrock | Stradbally | SE | OPW | 261420 | 199062 | 95 | 29 |
| 14019 | Levitstown | Barrow | SE | OPW | 270623 | 187609 | 1697 | 55 |
| 15001 | Annamult | Kings | SE | OPW | 254289 | 144376 | 444 | 37 |
| 15003 | Dinin Bridge | Dinin | SE | OPW | 247880 | 162807 | 299 | 37 |
| 15006 | Brownsbarn | Nore | SE | OPW | 261699 | 139098 | 2418 | 37 |
| 16008 | New Bridge | Suir | SE | OPW | 200220 | 134149 | 1090 | 55 |
| 16009 | Caher Park | Suir | SE | OPW | 205297 | 122870 | 1583 | 56 |
| 18002 | Ballyduff | Blackwater | SW | OPW | 196410 | 99140 | 2334 | 54 |
| 18003 | Killavullen | Blackwater | SW | OPW | 164710 | 99738 | 1257 | 37 |
| 18005 | Downing Bridge | Funshion | SW | OPW | 182294 | 101821 | 379 | 37 |
| 18006 | Cset Mallow | Blackwater | SW | EPA | 152546 | 97448 | 1055 | 32 |
| 18050 | Duarrigle | Blackwater | SW | EPA | 124987 | 94359 | 249 | 28 |
| 19001 | Ballea | Owenboy | SW | OPW | 170971 | 63276 | 103 | 37 |
| 21002 | Coomhola | Coomhola | SW | EPA | 99825 | 54901 | 65 | 34 |
| 23002 | Listowel | Feale | SH | OPW | 99700 | 133295 | 647 | 49 |
| 25001 | Annacotty | Mulkear | SH | OPW | 164265 | 157679 | 648 | 36 |
| 25002 | Barrington's Bridge | Newport | SH | OPW | 167908 | 154908 | 222 | 56 |
| 25006 | Ferbane | Brosna | SH | OPW | 211536 | 224406 | 1163 | 54 |
| 25030 | Scarriff | Graney | SH | OPW | 164180 | 184277 | 280 | 37 |
| 26009 | Bellantra Bridge | Black | SH | OPW | 212848 | 289416 | 91 | 37 |
| 26021 | Ballymahon | Inny | SH | OPW | 216107 | 256987 | 1099 | 34 |
| 26029 | Dowra | Shannon | SH | EPA | 199064 | 326947 | 117 | 34 |
| 27002 | Ballycorey | Fergus | SH | OPW | 134431 | 180323 | 511 | 55 |
| 32012 | Newport Weir | Newport | W | EPA | 99773 | 294400 | 146 | 28 |
| 34001 | Rahans | Moy | W | OPW | 124367 | 317782 | 1975 | 35 |
| 35002 | Billa Bridge | Ballysadare | W | OPW | 163926 | 325739 | 81 | 37 |
| 35005 | Ballysadare | Ballysadare | W | OPW | 166832 | 329046 | 640 | 63 |
| 36010 | Butlers Bridge | Annalee | NW | OPW | 240817 | 310466 | 772 | 38 |
| 38001 | Clonconwal Ford | Owenea | NW | OPW | 176584 | 392714 | 111 | 37 |
| 39006 | Claragh | Leannan | NW | EPA | 220215 | 420084 | 245 | 32 |
| 201005 | Camowen Terrace | Camowen | NW | NI | 246071 | 373048 | 277 | 37 |
| 201008 | Derg | Castlederg | NW | NI | 226512 | 384216 | 335 | 33 |
| 202002 | Faughan | Drumahoe | NW | NI | 246411 | 415098 | 273 | 33 |
| 203028 | Agivey | Whitehill | NB | NI | 288337 | 419362 | 101 | 37 |
| 203042 | Crumlin | Cidercourt Bridge | NB | NI | 313468 | 376536 | 55 | 28 |
| 204001 | Bush | Seneirl Bridge | NE | NI | 294191 | 436250 | 299 | 37 |
| 205008 | Lagan | Drumiller | NE | NI | 323635 | 352493 | 85 | 35 |
| 206001 | Clanrye | Mountmill Bridge | NB | NI | 308536 | 331026 | 120 | 35 |

Org: monitoring organization; RBD: River Basin District (NB: Neagh Bann, E: Eastern, SE: Southeastern, SW: Southwestern, SH: Shannon, W: Western, NW: Northwestern, NE: Northeastern and NI: Northern Ireland).

the IAMAX series, all subsequent analysis is based on in-filled series.

## 3.2 Trend detection

Time series of each indicator were analysed for trend using two widely-applied tests; for brevity we direct the reader to the literature for more in-depth descriptions. The Mann-Kendall (MK) test for monotonic trend (Kendall 1975) is a non-parametric rank-based method that is widely applied in hydrological trend studies (e.g. Hannaford and Marsh 2008, Hu *et al.* 2011). The standardized MK statistic, $Zs$, follows the standard normal distribution with a mean of zero and variance of one. A positive (negative) value of $Zs$ indicates an increasing (decreasing) trend. Statistical significance of trends is evaluated with the probability of Type I error set at the 5% significance level. A two-tailed MK test was chosen, hence the null hypothesis of no trend (increasing or decreasing) is rejected when $|Zs| > 1.96$.

Trend magnitudes were estimated from the slope of the Theil-Sen Approach (TSA) (Theil 1950, Sen 1968) in order to corroborate and map trends detected by the MK method. The TSA is more robust to outliers compared to parametric tests such as linear regression. The slope estimator ($\beta$) is the median over all pairs of points in the time series (Helsel and Hirsch 1992):

$$\beta = \text{Median}\left(\frac{y_j - y_i}{x_j - x_i}\right) \quad \text{for all } i < j \text{ and } i = 1, 2, \ldots (n-1); \quad j = 2, 3, \ldots n \tag{1}$$

To allow comparison of trend magnitudes across all stations, the TSA slopes were calculated from time series of the standardized river flow. This standardized flow anomaly (SFA) (Déry *et al*. 2005) is given as:

$$\text{SFA} = \left(\frac{F_i - \overline{F}}{\sigma_F}\right) \tag{2}$$

where $F_i$ is the river flow value ($m^3$ $s^{-1}$) for a particular indicator for an individual year ($i$), $\overline{F}$ is the mean flow value for the indicator for the selected time period, and $\sigma_F$ is the standard deviation of $F$. Positive (negative) values of the SFA indicate above (below) average flow quantities for the particular time series. Déry *et al*. (2005) note that standardization allows direct comparison of river flow anomalies despite their large range in absolute values. Slopes calculated from SFA time series are expressed in standard deviations per year; this approach has also been used by Stahl *et al*. (2010).

Here, the application of statistical tests centres on the magnitude, direction and persistence of trends over time and not only the identification of statistically significant trends. We recognize that the robustness of significance testing for hydroclimatic indicators is increasingly questioned in the literature due to difficulties in establishing a valid null hypothesis and the impact of long-term persistence (e.g. Cohn and Lins 2005, Koutsoyiannis and Montanari 2007, Clarke 2010, Stahl *et al*. 2010). Statistical significance is tested for the MK test only; the dependence of the level of significance on the selected period of analysis is also examined.

### 3.3 Serial correlation

Hamed and Rao (1998) show how the existence of either positive or negative autocorrelation in a time series can confound detection of significant trends. Positive autocorrelation indicates persistence in the data and a tendency for consecutive dry or wet years. Hence, the presence of positive serial correlation in a data set increases the expected number of Type I errors, or false positive outcomes for the MK test (von Storch 1995), leading to a disproportionate rejection of the null hypothesis (no trend), when the null hypothesis is true; this increases the probability of detecting a statistical signifigcant trend when none may exist (Yue *et al*. 2002).

In line with other authors, emphasis is placed on the minimization of Type I errors (e.g. Bayazit and Önöz 2004, Hamed 2009). In order to assess the correlation structure of each indicator used in this study, autocorrelation function (ACF) plots were computed from the residuals of a linear regression model fitted to the data. From our analysis, only a minority of indicators in spring (5.4% of stations) and summer (16.2%) show statistically significant (5% level) positive lag-1 serial correlation.

For stations revealing serial correlation, block bootstrapping is employed so that the correlation structure is preserved. Önöz and Bayazit (2012) show that block bootstrapping in the presence of serial correlation ($r$) can affect the power of the MK test. For small samples ($n = 25$), the optimal block length ($L$) that makes the rejection rate closest to the desired significance level (in this case 5%) is $L = 4$ when $r \leq 0.3$ and $L = 4$ or 5 when $n \leq 50$ (Önöz and Bayazit 2012). Therefore, a block length of 4 was used to allow for serial correlation. In determining significance for bootstrapping, the distribution of the MK test statistic was estimated from 10 000 resamples where the null hypothesis was rejected when the MK *Zs* statistic of the original series is higher than the 9750th largest or lower than the 250th MK *Zs* statistic of 10 000 samples.

### 3.4 Study design

The analysis is based on two distinct approaches to testing for monotonic trends. First, we employ the fixed time period 1976–2009, chosen to optimize the record length *versus* the spatial distribution of stations. This strategy allows ready comparison of trends across the network and the ability to map the spatial distribution of results. To maximize station inclusion, we include all records that commence within three years of this period. Second, the persistence of trends is examined by systematically reducing the start year of analysis from the whole record to a minimum of 30 years following the approach of Wilby (2006). For each indicator, the MK *Zs* statistic was derived first for the full record, e.g. 1954–2009, then 1955–2009, and so on until 1980–2009 to give sample sizes ranging between 56 and 30 years. By plotting *Zs* values for each iteration of start years, a fuller appreciation of the evolution of trend can be achieved, as well as an indication of the persistence of any significant trends throughout the period of record.

The hydroclimatology of Western Europe is complex and has been shown to be affected by a number of modes of variability including the Atlantic Multidecadal Oscillation (AMO) (Knight *et al*. 2006), the Arctic Oscillation (AO) (Ambaum *et al*. 2001) and the El Niño Southern Oscillation (Wilby 1993) among others, and is susceptible to anomalies in sea-surface temperatures in the Atlantic (Sutton and Dong 2012). We assess the consistency of trends with the North Atlantic Oscillation Index (NAOI). The NAOI is the dominant mode of natural climate variability in western Europe, and has been shown to influence storm tracks over the region (Hurrell and Van Loon 1997). The winter NAOI is most discernible and exhibits significant inter-annual and inter-decadal variability (Hurrell 1995). As presented by Wilby *et al*. (1997), strong positive anomalies occurred from 1900 to 1930. From the 1930s to 1960s the index was relatively low. A strong positive trend persisted until the mid-1990s with wetter-than-normal conditions over northern Europe since 1980 linked to positive NAO conditions (Hurrel and van Loon 1997). Since the mid-1990s the NAOI has exhibited a negative trend culminating in 2009/2010 with one of the most negative NAOI anomalies on record (Pinto and Raible 2012).

To investigate the relationship between the winter (DJF) NAOI and selected flow indicators, we employ Spearman's rank correlation with the significance level of Rho set at 5%. NAOI series were obtained from the National Center for Atmospheric Research (NCAR; http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-station-based). Lagged correlations were also derived, in particular for summer mean flows, which were correlated with the previous winters' NAOI.

## 4 RESULTS

### 4.1 Fixed period 1976–2009

Results of the fixed period analysis are shown in Table 2. This gives the direction and the proportion of trends that were significant. All trends were derived using the conventional MK test with significance at the 5% level determined using statistical tables and block bootstrapping. Both approaches to significance testing yielded almost identical results and so only the conventional MK test is presented in Table 1. Only one station with serial correlation for SPmean flow is found to be non-significant when tested using block bootstrapping, supporting a view of low levels of serial correlation in the indicators. The spatial distribution of trends for each indicator is presented in Fig. 1, where the magnitudes of trends are shown as standard deviations per year. Significant trends (5% level), derived using the MK test are also plotted.

**Table 2** Direction and proportion of significant trends for fixed period analysis 1976–2009 for each indicator analysed. Results based on Mann-Kendall test with significance tested at the 5% level using statistical tables. Block bootstrapping was also employed to account for serial correlation but yielded almost identical results and is thus not shown.

| | No. of stations | Positive (%) | | Negative (%) | |
|---|---|---|---|---|---|
| | | Total + | Significant | Total – | Significant |
| ANmean | 37 | 64.9 | 2.7 | 35.1 | 2.7 |
| WImean | 37 | 32.4 | 0.0 | 67.6 | 2.7 |
| SPmean | 37 | 24.3 | 0.0 | 75.7 | 16.2 |
| SUmean | 37 | 97.3 | 13.5 | 2.7 | 0.0 |
| AUmean | 37 | 81.1 | 0.0 | 18.9 | 0.0 |
| IAMAX | 27 | 76.9 | 19.2 | 23.1 | 7.7 |
| MAX10 | 31 | 74.2 | 19.4 | 25.8 | 0.0 |
| MAX30 | 37 | 67.6 | 8.1 | 32.4 | 2.7 |

For ANmean flows for the period 1976–2009, 65% of stations in the IRN show increasing trends. However, the only significant trends are found in Northern Ireland, for stations in the UK Benchmark Network, with one increasing and one decreasing. The increasing trends with the highest magnitude are found for the northwest and the Upper Shannon basin. Stations in the south of Ireland show weak increasing and decreasing trends. In the Suir and Nore catchments in the southeast, all three stations show weak decreasing trends in annual mean flows. For WImean flows, increasing trends are largely confined to stations west of the Shannon basin, with the largest increases in the west and northwest. To the east and south trends in winter tend to be negative, with the largest negative trends in the northeast, south and southeast. Only one significant decreasing trend is found for WImean in the northeast. Overall, 67.6% of the stations show decreasing trends in WImean during the period of record.

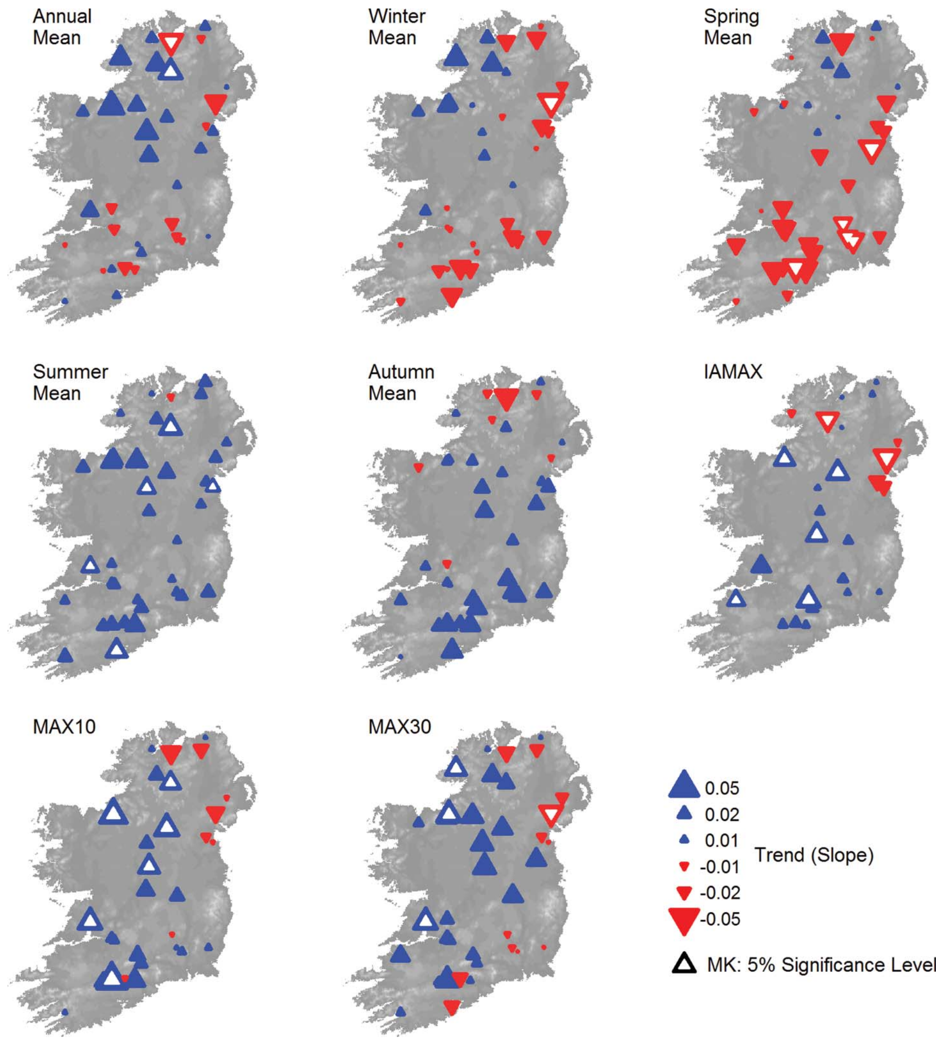


**Fig. 1** TSA trend slopes for each indicator analysed. Trends are given in standard deviations per year: ▼ represents decreasing trends and ▲ increasing trends. Significant trends (5% level) are shown by white triangles and derived from the MK test using the bootstrapping method.

The largest percentage of statistically-significant trends in mean flows is found for spring and summer mean flows. In spring, over 75% of stations show decreasing trends with 13.5% of these significant when serial correlation is accounted for (16.2% with conventional MK). None of the increasing trends are found to be significant. Weak increasing trends are largely confined to the northwest, while all stations in the south and east, and the majority of midland stations show strong decreasing trends. In the south and southeast these trends are particularly large.

In summer, almost all stations reveal increasing trends (97.3%) in mean flows, with 13.5% of stations showing statistically significant increases. There is no clear spatial pattern in the magnitude or significance of trends. In autumn, increasing trends dominate, with 81% of stations showing increasing trends. The largest of these are found in the south and southeast. Decreasing trends are found for some northern stations, the majority of which are weak. None of the autumn trends are significant at the 5% level.

High-flow indicators are dominated by increasing trends. For the instantaneous annual maximum flow (IAMAX), 77% of stations show increasing trends, 19% of which are significant. These significant trends are located in the southwest, west and Upper Shannon basin. Stations in the northwest and northeast show decreasing trends, two of which are significant. Weak increasing trends are also evident for some of the midland and southeastern stations.

For the longer duration high flows, MAX10 shows increases for 74% of stations, 19% of which are significant. As with IAMAX, significant trends are prominent in the southwest, west and Upper

Shannon basin. Stations in the north and northeast show non-significant decreasing trends; conversely, weak increasing trends are evident in the southeast. This spatial distribution is similar for MAX30, with one significant decreasing trend in the northeast. The number of significant trends for MAX30 is also less and confined to the Atlantic margin. A large number of increasing trends are also evident for the Upper Shannon region and southwest, whereas weak decreasing trends are found for the southeast.

For the fixed period of analysis, the relationships between the winter (DJF) NAOI and selected flow indicators are assessed using correlation analysis. Figure 2 shows the results of this analysis. WImean flows are significantly correlated (5% level) with the winter NAOI, particularly for stations in the southwest and northwest. Stations along eastern and southern coastal areas show non-significant negative correlations. SUmean flows throughout the country show negative correlations with the previous winter's NAOI index, with stations in the south and southeast showing significant negative correlations. This relationship has also been identified for stations in the east and southeast of the UK (Wedgbrow *et al.* 2002). For MAX30 day flows, which are predominantly found in winter months, significant positive correlations are evident in the southwest and northwest. Further east, correlations become non-significant and non-significant negative correlations are found along the eastern seaboard.

## 4.2 Representativeness of fixed period

To visually inspect the role of variability across the network, river flow records for annual and seasonal means for all stations were standardized (using the SFA method described above) and smoothed using Local Polynomial Regression Fitting (LOESS). The "LOESS" function (with degree of smoothing parameter "span" set at 0.25) was implemented within the "stats" package in the R statistical computing programming language (R Development Core Team 2012).

The standardized and LOESS-smoothed seasonal mean flows are presented in Fig. 3. The number of stations included decreases prior to the mid-1970s due to the lower number of longer-record stations. Apparent is the coherence of inter-site variability across all stations and seasons. Increased inter-annual variability in flows was found since the early 1990s in winter. Positive anomalies are evident in spring flows from the mid-1970s to the mid-1990s. Summer and autumn show positive extremes in flow post-2006, most notably in summer due to the recent spate of wet years. It is clear from Fig. 3 that the time period of analysis has a large bearing on identified trends, emphasizing the need to place fixed-period analyses in the context of longer records.

## 4.3 Persistence of trends

Analysing the persistence of trends by varying start years allows a fuller understanding of the development of trends. Previous research highlights the influential role of outliers at the beginning or end of the record, particularly when records are short (Wilby *et al*. 2008). This is problematic here, where there are extremes at the end of the record, in particular for summer and autumn mean flows. To examine the sensitivity of trends throughout the record to these

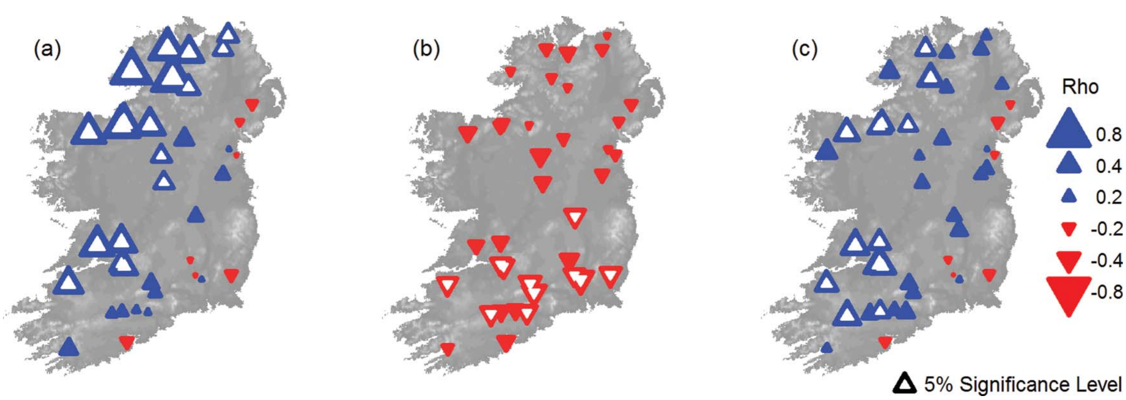


**Fig. 2** Spearman's rank correlation between: (a) winter flows and winter NAOI, (b) summer flows and preceding winter NAOI, and (c) MAX30 day flow and winter NAOI (right). ▲ and ▼ arrows represent positive and negative correlations, respectively. The size of arrows shows magnitude of correlations, while significant correlations at 5% significance level are shown by white filled arrows.

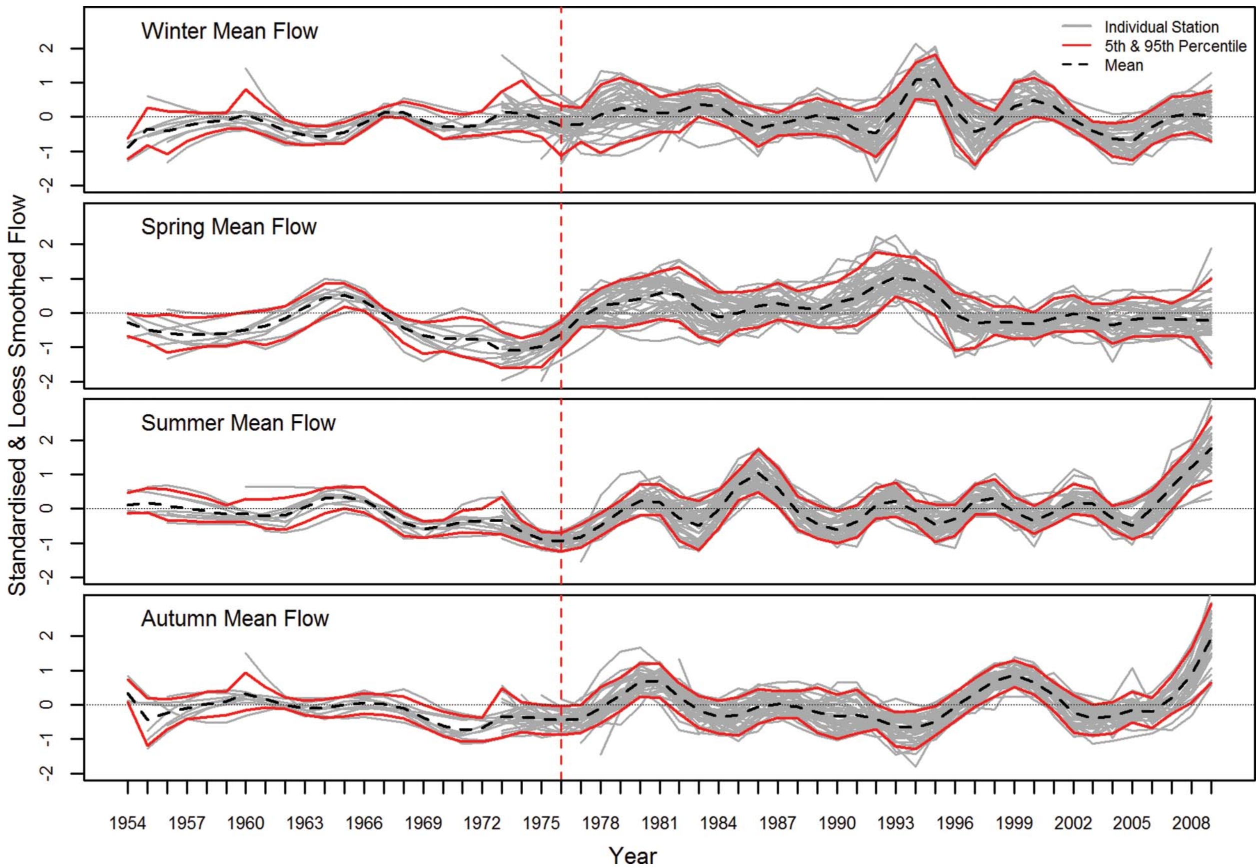


**Fig. 3** Standardized and LOESS-smoothed seasonal mean flows for stations across the network. Light grey lines are the standardized and LOESS-smoothed series for individual stations, solid (dark grey) lines are the 5th and 95th percentiles of the standardized and smoothed flows across all stations in the IRN, and dashed (black) line is the mean of the data set. The dashed vertical line represents the start of the fixed period 1976–2009.

extremes post-2006, the persistence of trends ending in 2006 as well as 2009 was calculated. Results for annual and seasonal mean flows are presented in Fig. 4, and for high-flow indicators in Fig. 5. In both figures, the left-hand column represents the end year of 2009 and the right-hand column the end year of 2006.

For trends ending in 2009, the majority of ANmean flow records show increasing trends across Ireland that have a higher level of significance (stronger trends) with earlier start years. However, there is evidence of a major change in the magnitude and direction of trends across the network post mid-1970s where significance is lost. Even stations with significant increasing trends throughout the record show a shift to decreasing trends by the late 1970s. WImean flows show a lack of statistically significant trends throughout the record, but there is a tendency towards stronger positive trends with increasing record length. There is a consistent pattern across the network of a likelihood of weaker positive trends or decreases in more recent decades. In particular, for stations in the southwest and the Neagh-Bann basin, there is a tendency for strong and significant negative trends in WImean commencing after the mid to late 1970s. Stations in the southeast of the country have gone from strongly positive trends for start years before the mid-1960s, to negative trends after the mid-1970s.

SPmean flows display considerable variation and large changes in the direction and significance of trends. Earlier start years display a tendency for strongly positive trends. However, tests commencing in the early 1960s show tendencies for weak positive or negative trends before showing increases again for later start years. However, there is a considerable change in direction, with spring trends becoming significantly negative for many stations for start years after the mid-1970s. Some of the largest shifts in spring are experienced in the southeast of the country.

SUmean flows show persistent positive trends, with particularly significant increases for early start

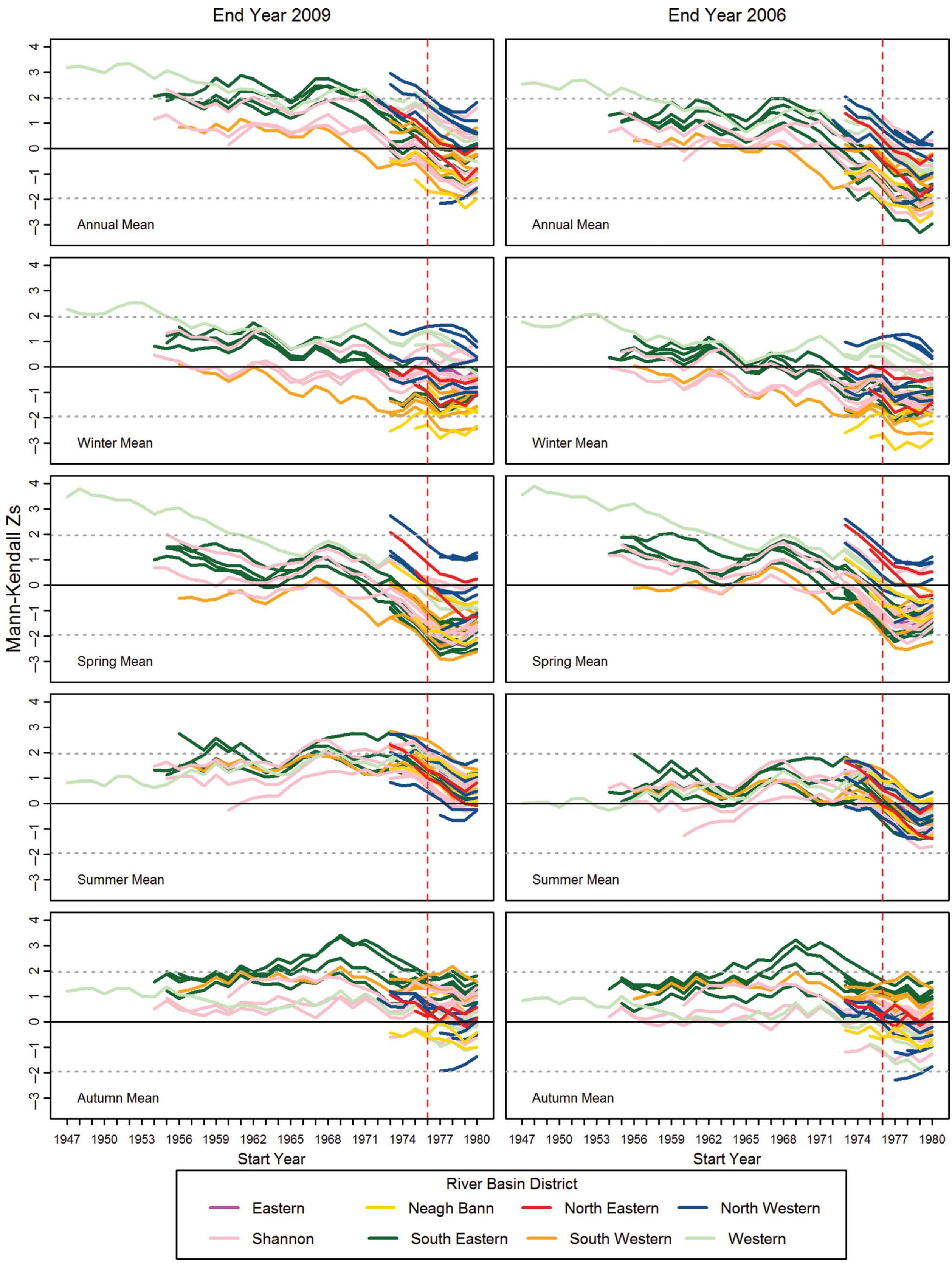


**Fig. 4** Persistence plots for annual and seasonal mean flows for trends ending in 2009 (left) and 2006 (right). Solid lines represent MK *Zs* statistics for varying start years for individual stations in the IRN. Dashed lines represent the threshold for significant trends at 5% significance level with statistics lying above (below) these indicating significant increasing (decreasing) trends since the corresponding date. The vertical red line marks the beginning of the fixed analysis 1976–2009.

years in the southeast. Extended drought conditions in the early 1970s weaken the magnitude and significance of trends from this period onwards. In addition, the persistence of increasing trends throughout the record for the majority of stations is likely to be an artefact of extremes at the end of the record. For autumn mean flows, trends are less subject to variability, but the impact of the mid-1970s low flows is also visible, most notably in the southeast.

In order to shed light on the importance of extremes at the end of the record, the persistence of trends ending in 2006 is shown in the right-hand column of Fig. 4. It is evident that end-of-record extremes have a significant impact on the strength and significance of trends in many of the flow indicators and affect even the longest records. For the analysis ending in 2006, there is a large reduction in the number of significant positive trends in summer, and a greater proportion of negative trends, particularly since the mid-1970s, compared to trends ending in 2009. With the exception of stations in the west and northwest, winter mean flows also show a higher proportion of negative trends when extremes at the end of the record are removed. Therefore, for both WImean and SUmean flows, there is a notable lack of significant trends throughout the network with even the direction of trends highly dependent on the start and end year of analysis. Spring and autumn means are least affected by end-of-record extremes, yet there is still a high degree of variability in the evolution of trends.

Figure 5 shows persistence plots for high-flow indicators. Records ending in 2009 have persistent positive trends in each of the high-flow indicators, particularly for earlier start years. Strong significant trends are apparent in IAMAX for stations in the southeast, the Shannon basin and the west, and particularly for trends beginning prior to the 1970s. Some decreasing trends are found in the northeast and Neagh-Bann, along with two stations in the northwest (although the brevity of records for the latter should be noted). For longer-duration high flows, MAX10 also shows persistent positive trends for the majority of stations. Persistent significant trends are evident over the full record for Ballysadare in the west and for Ballycorey in the Upper Shannon basin. Large positive trends are also evident for the southeast beginning in the mid-1950s and early 1970s.

Similar results are evident for MAX30 flows. Strong positive trends are associated with early start dates, again emphasizing the importance of longer records for contextualizing results based on shorter periods. There is a decrease in the strength and significance of IAMAX and MAX30 trends for more recent decades. For trends ending in 2006 (Fig. 5 right), it is apparent that IAMAX is also influenced by extremes at the end of the record. While trends remain strongly positive for many stations, there are fewer stations with significant trends in more recent decades when the effect of end-of-record is removed. Longer-duration high-flow indicators are less sensitive to outliers at the end of the record suggesting a greater robustness of trends in these variables.

## 5 DISCUSSION OF RESULTS

This paper introduces and describes a reference network of river flow stations for climate change monitoring, detection and attribution in Ireland. Our analysis shows that, despite evidence of statistically-significant trends for some time periods, particularly for longer records, there is a lack of persistent significant trends in annual and seasonal mean flows. Trends show strong coherence across the island, particularly for mean flows. This coherence, coupled with the nature of the IRN, i.e. the limitation of land-use change for which information exists, suggests that the trends are climate-driven. However, Merz *et al*. (2012) call for more effort and scientific rigour in attributing detected trends in river flows by gathering evidence of change that is consistent with an assumed driver, evidence of detected changes that are explained by alternative drivers, and by attaching confidence levels to the attribution statement. In the following discussion, we move towards what Merz *et al*. (2012) term soft attribution by examining the consistency/inconsistency of trends with assumed drivers.

To examine the consistency of trends in seasonal mean runoff, rainfall trends were analysed for eight long-term precipitation records. Persistence plots with varying start years of analysis for seasonal precipitation totals are shown in Fig. 6. The strength and coherence of trends in precipitation reveal close agreement with river flows; in particular, in winter there is a lack of long-term statistically significant positive trends, while summer shows weak positive and negative trends. Long records for spring show a tendency for positive trends with the same transition to negative trends evident in recent decades. Such consistency with precipitation, together with the minimization of confounding factors in the hydrometric reference network, increases confidence that the influence of internal catchment

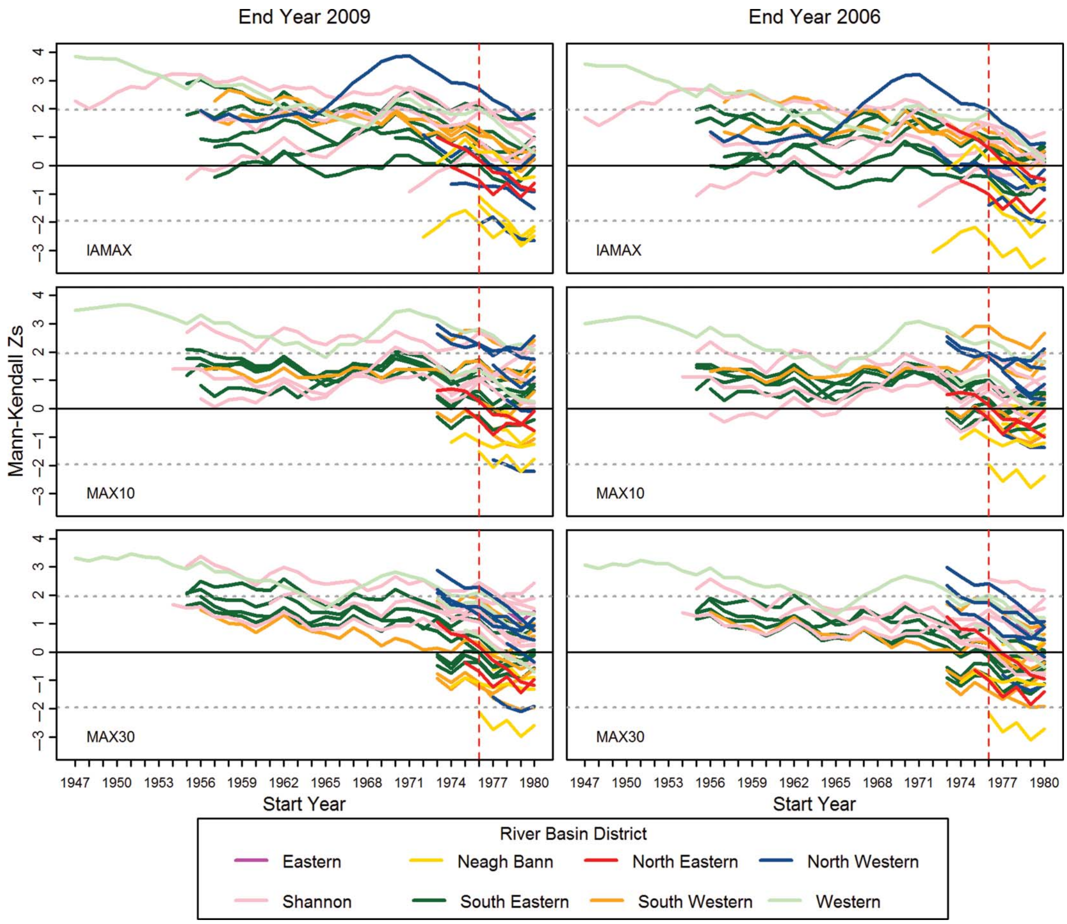


**Fig. 5** Persistence plots for high-flow trends ending in 2009 (left) and 2006 (right). Solid lines represent MK *Zs* statistics for varying start years for individual stations in the IRN. See Fig. 4 for explanation.

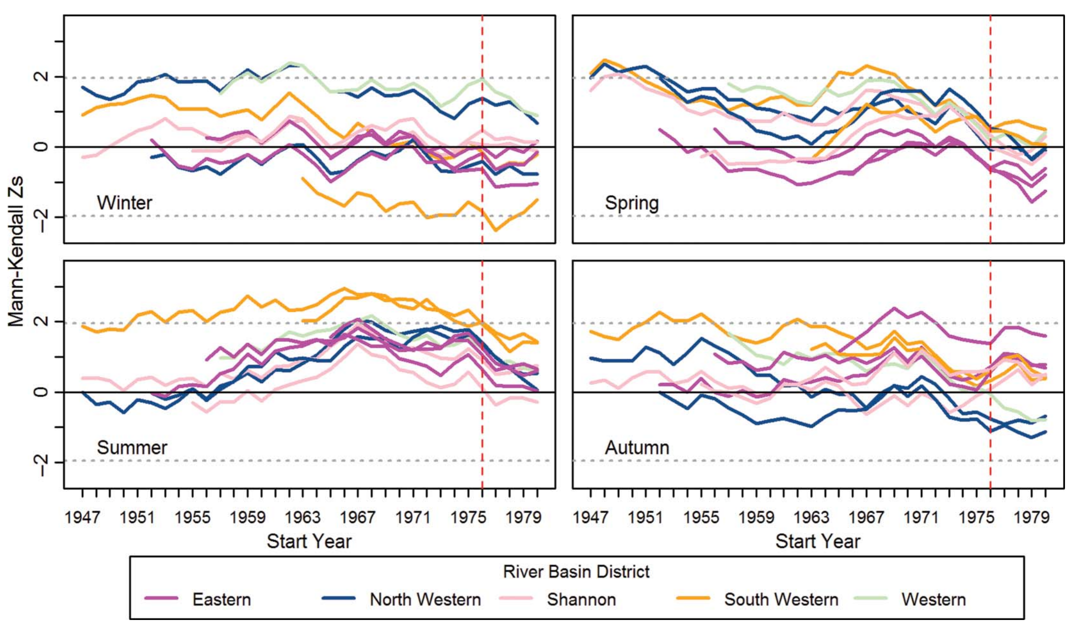


**Fig. 6** Persistence of trends in precipitation totals (mm) for eight rainfall stations across Ireland. Solid lines represent MK *Zs* statistics for varying start years for individual rainfall stations. See Fig. 4 for explanation.

changes, such as land-use change, are not the primary driver of change. However, it should be noted that the lack of long-term, rigorous metadata on land-use change means that its influence cannot be entirely ruled out, although we are unaware of any systematic land-use changes at a scale that would influence trends across the network.

Trends in seasonal mean flow from the IRN are also highly consistent with results from the UK Benchmark Network (Hannaford and Buys 2012) and with Dixon *et al*. (2006), who reported for Wales a dearth of significant trends around the means of the flow distribution, with the highest number of significant trends identified at the tails of the flow distribution. Regional similarities of results with the UK, and the coherence of trends in both river flows and precipitation records in Ireland support the view that the stations selected for the IRN are fit for purpose and add confidence that the trends are being forced by a common climate driver. However, as noted by Merz *et al*. (2012), further rigour is needed for more formal "hard" attribution of specific drivers.

The large transition in the magnitude and direction of trends in SPmean flows is surprising given the findings of Kiely (1999) and Leahy and Kiely (2011) for increases in March flows and precipitation in recent decades. Differences in methodological approaches offer some insights where previous work has examined changes before and after the NAOI change point of the mid 1970s, whereas here the evolution of trends over time is analysed. The LOESS plots in Fig. 3 also show the change point in spring flows in the mid-1970s as identified by Kiely (1999), with high spring mean flows continuing until the mid-1990s. However, it is apparent that SPmean flows have decreased since the mid-1990s. This shift is likely to be responsible for the transition from increasing to decreasing trends experienced in spring and is consistent with more negative NAOI anomalies since the mid-1990s.

Mean and high flows do not necessarily show the same direction of trend, underlining the importance of careful selection of indicators for analysis. For the fixed period analysis, decreases are found for winter mean flows in contrast to increasing trends in IAMAX and MAX10 flows. Even for longer records, trends in high flows are stronger than for winter means. These findings tie in with evidence of increases in heavy rainfall days identified for Ireland (Leahy and Kiely 2011). The strong and persistent positive trends in high-flow indicators provide evidence against the assumption of stationarity in flood series.

Although there is evidence of climate variability and change in the IRN records, it is more difficult to attribute these to anthropogenic climate change. For the fixed period of analysis (1976–2009) there is a strong tendency for observed trends to contradict those expected for future anthropogenic climate change scenarios of wetter winters and drier summers. In winter, shorter records show widespread decreasing trends in mean flows; however, there is a tendency for positive trends when longer records are analysed. When examining the persistence of trends, the contradiction in summer mean flows is evident even for the longer records in the IRN. Trends in summer mean flows are sensitive to extremes at the end of the record; however, when these are removed there remains little evidence of persistent decreasing trends. Such contradictions in summer mean flows have also been reported for the UK (Hannaford and Buys 2012). Previous studies have indicated that a lack of evidence of anthropogenic climate change signals may be due to the low signal-to-noise ratio of climate change compared to natural climate variability (e.g. Wilby 2006, Hannaford and Marsh 2008, Wilby *et al.* 2008, Fowler and Wilby 2010). In this study, summer flows show the highest variance of the indicators examined. The findings of Sutton and Dong (2012) that warming of North Atlantic sea-surface temperatures are associated with wetter summers in this part of Europe also have relevance here. This transition from cool (1960s) to warm (since the 1990s) phases could account for the unexpected (but perhaps temporary) wetting of summers contrary to long-term climate model projections.

Trends in many of the indicators analysed show correlations with the winter NAOI, particularly along the Atlantic margins for high flows, winter and spring means. Elsewhere, Villarini *et al*. (2012) show for many stations in Austria that the NAOI is an important predictor of the number of large floods, while Hannaford and Marsh (2008) showed that high flows in the western UK are highly correlated with the NAOI. These findings indicate the importance of understanding of NAOI response to greenhouse gas (GHG) forcing.

However, there is considerable uncertainty as to how anthropogenic GHGs have contributed to NAOI variability in the latter part of the 20th century and about the potential influence of GHGs on future NAOI (and hence Irish rainfall–runoff). Dong *et al.* (2011), using an atmosphere-only model, indicated that GHG forcing may have played an important role in the NAOI variability and climate anomalies during the 20th century. Conversely, Osborn (2004) showed, using a coupled-model comparison of seven atmosphere–ocean general circulation models (AOGCMs), that observed NAOI trends of the past decades can be explained by internally generated variability and a small GHG forcing. Similarly, Stephenson *et al*. (2006), using the CMIP2 ensemble, also highlighted the inability of AOGCMs to capture the observed decadal variability in NAOI. Their findings suggest that future NAOI response to heightened GHG concentrations is small and highly model dependent, with the NAOI unlikely to be a key contributor to predicted increases in winter precipitation in Europe. Rather, Stephenson *et al.* (2006) suggest that projected temperature and precipitation patterns for Europe will be controlled by thermodynamic processes where warmer conditions influence the positioning of storm tracks.

In terms of assumed drivers of change in observations, our analysis finds that the historical development of the hydrometric monitoring network itself can have a large influence on the trends derived, particularly for summer mean flows in the Irish case. Records for the majority of stations in Ireland (and the UK) commenced in the early to mid-1970s in response to the water management priority of dealing with drought conditions at this time. Therefore, records for summer are marked by extremes at both the beginning (low) and end (high) of records which "hard wires" positive trends into results. Such historical issues are also important to consider in reconciling differences between observations and climate scenarios. Slight changes to the period of record analysed therefore result in substantial changes in the trends derived for summer.

The extent of variability is also problematic for the analysis of fixed periods in which the direction, strength and significance of trends are highly dependent on the period chosen for analysis. For example, spring flows at individual stations can show significant increasing trends, while decreasing trends can be found in the same indicator for series commencing only a decade later. These findings, again, emphasize the importance of longer records for contextualizing results that may otherwise be biased by the design and timing of the network installation, and the care required when communicating results from fixed-period analyses that are conditional on the chosen time period. Examining persistence and evolution of trends over time potentially increases the scope for linking to assumed drivers.

## 6 CONCLUSIONS

This study introduces and describes a reference network of river flow gauges for routine monitoring and detection of climate-driven changes and provides a first detailed analysis of trends in river flows for stations across the island of Ireland. Such networks increase confidence in trend attribution through the minimization of confounding factors. The development of an Irish reference network fills a significant gap in many European-scale trend studies; it is an important location for understanding climate variability and change on the Atlantic fringe of Europe. There is considerable spatial coherence in the evolution of trends, indicating that the Irish network is fit for purpose. Strong similarities emerge from trends in mean flows found in the UK and Ireland, which along with coherence with rainfall increases confidence that the detected trends are predominantly climate driven.

Due to large inter-annual variability, it is difficult to discern the expected anthropogenic climate change signal from observations at this point in time. Indeed, some of the trends identified are at odds with simulated impacts of climate change. We find that decreases in winter mean flows are a manifestation of the chosen time period (1976–2009) with longer records revealing increasing trends. However, even with longer records summer mean flows appear to be increasing, contrary to the expectation of regional climate models. While increasing summer trends are not as strong when end-of-record extremes are removed, there remains a dearth of significant decreasing trends. Spring mean flows show strong but variable trends with a large transition in the direction (positive to negative) and significance of trends evident for recent decades. High flows show strong and persistent positive trends, particularly for longer records, that are consistent with changes in extreme rainfall. This suggests that high flows are less affected by variability and may provide earlier climate change signals than mean flows.

The results highlight the dangers of using fixed periods for trend analysis, recognizing that there is always a trade-off between record length, network density and geographic coverage. From our analysis, most indicators (with the exception of summer and autumn mean flows) show a tendency for increasing trends with earlier start years. The results from the fixed period (1976–2009) are more susceptible to outliers in the record and dependent on the historical development of the monitoring network. Approaches based on the persistence of trends offer more insight into the development and drivers of trends than fixed periods of record, but are still influenced by outliers, particularly at the end of the record.

These results also have wider societal relevance. Most important is the danger of basing long-term climate change policy on short records that may be dominated by weak signals in river flows, large variability and non-stationarity. Given the lack of clear climate change signals and the conflicting trends in some indicators, further work is needed to identify stations and indicators that are more likely to provide early detection of anthropogenic climate change in the presence of large variability, keeping in mind that it may be several decades before a significant signal emerges (Ziegler *et al*. 2005, Wilby 2006).

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