01 - HYDRODETECT: THE IDENTIFICATION AND ASSESSMENT OF CLIMATE CHANGE INDICATORS FOR AN IRISH REFERENCE NETWORK OF RIVER FLOW STATIONS – AN OVERVIEW.

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Abstract

This paper provides an overview of key findings from the EPA funded HydroDetect project which establishes an Irish Reference Network (IRN) of river flow gauges for monitoring and detecting climate driven trends. The flow archive from 35 hydrometric stations has an average record length of 40 years and draws from the strengths of the existing national hydrometric network. Using criteria based on the quality of flow records and minimisation of artificial influences and land-use change, complimented by expert judgement, the IRN is a valuable resource facilitating more strategic monitoring of climate driven variability and change in hydrological indicators and enabling more confident attribution of detected trends. Here an analysis of trends in mean and high flows for stations in the IRN is presented, with the spatial distribution of trends across the network examined for the period 1976-2009. The following key findings emerge. While there is considerable evidence of change in the IRN, it is difficult at this point in time to attribute these to anthropogenic greenhouse gas induced climate change. Indeed some of the trends identified – decreases in shorter records in winter mean flows and increases in summer flows – are not consistent with expected changes as simulated by Global Climate Models. This should not be surprising given the large variability of river flows relative to climate change signals at this point.

Trends in Irish river flows are strongly correlated with the winter North Atlantic Oscillation Index (NAOI). The sensitivity and response of the NAO to greenhouse gas forcing will have obvious implications for Irish hydrology; however the question remains open as to the impact that greenhouse gas forcing has had on recent behaviour of the NAO and how it is likely to respond to future forcing. While it remains challenging to identify anthropogenic climate change signals at the catchment scale due to large natural variability and therefore a low signal to noise ratio, there is high potential for identifying sentinel stations and indicators within the IRN for early detection of climate change signals. These findings heighten the importance of the IRN for monitoring and detecting climate change signals at the catchment scale, for tracking the emergence of signals relative to natural variability and for providing information, free from confounding factors, for validating output from climate change impact assessments and developing adaptation policies.

This paper provides a summary overview of key findings from the EPA funded project Hydrodetect. Interested readers are encouraged to view the full project report for details. The report is available at [*http://www.epa.ie/pubs/reports/research/climate/CCRP_27.pdf*](http://www.epa.ie/pubs/reports/research/climate/CCRP_27.pdf).

1. INTRODUCTION

Early detection of climate change signals in hydrological regimes is important for informing adaptation strategies and contexualising uncertain simulations of future impacts assessments. River flow archives hold vital information for evidence based assessments of hydrological variability and change (Marsh, 2002; Hannah *et al.*, 2011). Over the past 15 years a growing number of countries have invested in Reference Hydrometric Networks (RHNs) in order to collect data that is minimally impacted by confounding human influences (Stahl *et al.*, 2010). The primary aim of these networks is to provide a data source to effectively identify, quantify and interpret hydrological change (Marsh, 2010). While data requirements can be demanding, RHNs provide a more reliable basis for detecting climate variability and change and 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 contextualising trends from recent decades.

The overarching aims and objectives of this work are to

1. Identify a reference network of hydrometric stations from the current network of river flow gauges in Ireland, which can be used to monitor and detect climate driven changes in river flows.
2. Analyse trends in selected indicators to explore how climate driven trends have evolved in flow records for stations in the reference network.
3. Examine the potential for sentinel stations within the network and 'early-bird' indicators that are likely to show the earliest statistical detection of anthropogenic climate change signals.

2. IDENTIFICATION OF AN IRISH REFERENCE NETWORK

Criteria for the development of hydrometric reference networks include the degree of basin development, the absence of river regulation, long record length, station longevity and data accuracy (Pilon and Yuzyk, 2000). Ideally in terms of basin development reference stations should be pristine or have stable land-use for the period of record included. Large flood events or continuous erosion over time can alter the cross section of rivers, affecting flow ratings while seasonal weed growth can affect ratings during low flow and drought conditions. River regulation can include diversions, impoundments, abstractions and changes to channel morphology. Such confounding factors can heavily influence different parts of the flow regime of a catchment and significantly hamper the detection of climate change signals. Given the pervasive impacts that human activities Whitfield *et al.* (2012) highlight that emphasis must be placed on capitalising effectively on the existing hydrometric network. Additionally, in realising the full potential of existing hydrometric networks, compromises are often necessary for inclusion of representative catchment types and to ensure adequate spatial coverage. For example, UK Benchmark Network catchments are considered 'near natural' where the net impact of abstractions and discharges are within 10 percent of the natural flow at, or in excess of the Q95 exceedance threshold (flow exceeded 95 percent of the time) (Bradford and Marsh, 2003).

Similarly, for other criteria subjectivities are involved. The record length that can be obtained from reference networks depends on the legacy and foresight of historical investments in monitoring. Decadal and inter-decadal climate variability affects the direction, magnitude and timing 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). However, only selecting stations with greater than 50 years of data would dramatically reduce the number of stations available for inclusion and limit the spatial representativeness of any reference network. Therefore, 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 (Whitfield *et al.* 2012).

Following an extensive review of the literature and taking account of available metadata in Ireland, the following are key selection criteria for inclusion in the Irish Reference Network were employed:

1. Good and consistent hydrometric data quality (particularly at extreme flow ranges), as determined by hydraulic conditions at each site (i.e. stable control and accurate rating curves).
2. Near natural flow regime - zero or stable water abstractions.
3. Long record length (minimum 25 years).
4. Limited land-use change influence (≤ 2.5 percent of catchment area developed).
5. Stations must be representative of Irish hydrological conditions and climatic regions with good geographical coverage, ensuring that stations from each of the 8 Water Framework Directive (WFD) River Basin Districts (RBDs) covering the island are included.
6. Consultation with principal hydrometric agencies, including the Environmental Protection Agency and the Office of Public Works (OPW) in Ireland.

For geographical coverage stations from Northern Ireland that are part of the UK Benchmark Network were also included through consultation with the Rivers Agency of Northern Ireland, and the National River Flow Archive (NFRA) at the Centre of Ecology and Hydrology (CEH). Hydrometric rating quality was assessed using the quality categories employed by each hydrometric agency. Plots were produced to examine the prevalence of good quality flow measurements throughout each individual flow series. In addition, use was made of the ratings given to hydrometric stations as part of the Flood Studied Update (FSU) for Ireland. Finally, in determining the quality and stability of flow ratings expert advice was sought from responsible personnel in the hydrometric divisions of both the EPA and OPW while a questionnaire was circulated to local hydrometric teams to elicit local knowledge on gauging sites and hydrometric performance.

In some circumstances it was necessary for rules to be relaxed in order to capitalise on the existing network. Where a station had poor quality data for a particular part of the flow regime, the corresponding indicators were not analysed. 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. To ensure that stations were not overly influenced by abstractions and discharges expert consultation was sought while data on abstraction volumes were obtained from ‘The Provision and Quality of Drinking Water in Ireland – A Report for the Years 2007–2008’ (EPA, 2009) and from the ‘National Abstractions Further Characterisation Project’ for the Water Framework Directive conducted by CDM (2009). Rather than omit stations with abstractions, stations were identified as near natural where the net impact of abstractions and discharges are within 10 percent of the natural flow at, or in excess of Q95 (the flow exceeded 95 percent of the time).

The biggest confounding factor in Ireland is arterial drainage. Avoidance of arterial drainage was particularly challenging given such widespread installation to improve agricultural land drainage and reduce flood risk. Arterial drainage has resulted in the deepening and widening of river channels (Bhattarai and O'Connor, 2004). 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) for the UK. In aiming for adequate spatial coverage, stations were selected for each of the Water Framework Directive River Basin Districts (RBD). In addition, stations from Northern Ireland that are part of the UK Benchmark Network were also included to ensure all island coverage.

Figure 1 shows the derived Irish Reference Network for climate change monitoring and detection. In total 35 stations were identified for inclusion in the IRN from Ireland, plus a further 8 from the UK Benchmark Network. For the 35 Irish stations, the average record length is 40 years with a minimum of 28 and the longest 63 years. This record length is quite satisfactory and comparable to the average record length in the UK Benchmark network of 35 years (Whitfield *et al.*, 2012). Catchment areas range between 65 and 2460 km^2 with an average of 788 km^2. In comparison to other reference networks this is quite large, where Burn *et al.* (2012) highlight that average catchment area in RNs are approximately 500km^2. Full details on each of the stations is provided in Murphy et al. (2013a).

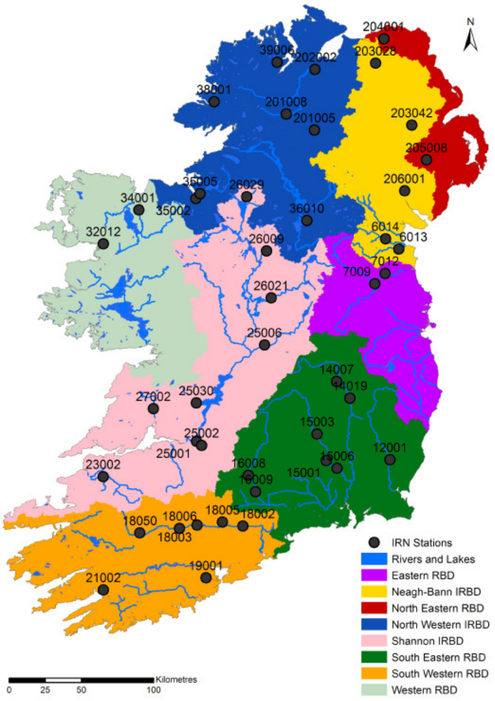


***Figure 1:** The spatial distribution of stations selected as part of the Irish Reference Network (IRN) and the Northern Irish stations in the UK Benchmark Network.*

It is important to view the development of the IRN as an iterative process. While the stations included have been assessed against the available metadata and in consultation with hydrometric agencies, the network should be reviewed in tandem with wider network reviews. It is possible that with the addition of new metadata, extreme hydrological events or a continued lack of funding for hydrometrics, that stations may fall out of the network. Indeed, with the passage of time new stations that are currently considered too short will be added to the network. While good spatial coverage has been achieved for much of the island, there is a notable gap in coverage for both the west and east of the island. In both of these locations it was difficult to find stations that met the established criteria, even when rules were significantly relaxed. A number of sites in the east were found to be of good quality but record length was too short for inclusion. In the fullness of time these sites will make a useful contribution.

Given the historical development of hydrometric monitoring in Ireland, the majority of stations commence in the 1970s. This results in a large number of stations with ~40 years of record. It is therefore imperative that longer records are protected and maintained. While there are more longer records in Ireland than selected for inclusion in the IRN, many have been heavily impacted by arterial drainage. The identification of a number of longer record stations in the network is an obvious advantage to the IRN, however long record stations are not widely distributed throughout the country, with the greatest number of stations located in the southeast of the country. From a strategic and management perspective, the identification of stations as part of the IRN enables more focused investment in monitoring during economically challenging times when emphasis is being placed on rationalising the national hydrometric network. The added utility of climate change monitoring increases the strength of argument that can be made promoting continued investment for these stations, while increasing their efficiency as multi-purpose sites.

3. ANALYSIS OF TRENDS FROM THE IRISH REFERENCE NETWORK

3.1 Indicators Analysed

Indicators for analysis were identified based on best international practice. Of importance was the selection of indicators that represent the full range of flow conditions. Within the broader HydroDetect project 22 indicators representing the full range of flow conditions were analysed. Here a subset of seven indicators representing mean and high flow conditions are presented and include:

- ***Annual Mean Flows (AN_Mean):*** Mean of daily mean flows (Dec-Nov) with Dec taken from the previous year.
- ***Seasonal Mean Flows***: mean of the daily mean flows for each season – W(Dec from the year before), SP, SU, A.
- ***Instantaneous Annual Maximum Flow (IAMAX):*** Maximum flow value in each water year from instantaneous flow data.
- ***MAX10:*** Highest 10-day consecutive daily mean flows in each water year.

3.2 *Methods for trend analysis*

The Mann-Kendall (MK) test for trend (Kendall, 1975) which is a rank based, non-parametric test for monotonic (linear) trend and has been employed in a large number of trend studies internationally (e.g. Hannaford and Marsh, 2008; Hu *et al.*, 2011). The test is based on the MK Zs statistic, standardised to a mean of zero and variance of one. For interpretation a positive Zs indicates an increasing trend, while a negative value denotes a decreasing trend. The magnitude of Zs reflects the strength of the trend. In applying trend tests attention is placed on the magnitude and direction of trends over time, in addition to evaluating the statistical significance of results. In evaluating significance we recognise the ongoing discussions in the literature regarding the difficulties of statistical testing in hydro-climatic variables. (See for example Koutsoyiannis and Montanari, 2007; Cohn and Lins, 2005; Clarke, 2010; Stahl *et al.* 2010)

In this paper statistical significance of trends is evaluated with the probability of type 1 error set at 5 percent (5 percent significance level). A two-tailed test is chosen, where the null hypothesis of no trend (increasing or decreasing trend) is rejected if $|Zs| > 1.96$. To assess autocorrelation for each of the indicators analysed, autocorrelation function (ACF) plots on the residuals of a linear regression model fitted to the time series were examined. Most indicators are not unduly affected by autocorrelation. There are indicators however, for which some stations show statistically significant (5 percent significance level) positive lag-1 serial correlation. The occurrence of autocorrelation is predominantly associated with low flows (see Murphy et al. 2013a).

3.3 Study Design – Moving Windows

Traditional approached to trend analysis are based on fixed time periods, often selected to optimize the record length versus the spatial distribution of stations. The benefits of such an approach include easy comparison of trends across a geographical area and the ability to map trends for the analysis of spatial variation in results. However, fixed/set periods are sensitive to the characteristics of the time period analysed, particularly to extremes at the beginning or end of the series and make it difficult to examine the evolution of trends over time. In addition, the trade-off of record length for geographical distribution limits the ability to place trends from shorter records in the context of longer term variability. Here a ‘moving windows’ method is employed to assess trends for all possible combinations of start and end years to a minimum of ten years. Such an approach facilitates a more thorough understanding of how the strength and timing of trends in stream flow indicators evolved across the county. It also facilitates the identification of directional changes versus more gradual trends that are important for assessing the role of climate forcings. The moving windows analysis is only conducted for the longer records in the IRN but results are representative of findings from the broader network.

4. RESULTS FOR SELECTED INDICATORS

4.1 Trends in Annual and Seasonal mean flows

Overall the results highlight the complexity associated with trends in mean flows – which are subject to large amounts of inter-annual variability in flow making the identification of persistent trends more difficult, particularly for short records and resulting in few significant trends. The following summary conclusions can be drawn for each indicator, see Murphy et al. (2013a) for full details on findings;

For annual mean flows *(Figure 2)* longer records tend towards statistically significant (5 percent level) increasing trends. Shorter records show non-significant decreases. No clear spatial distribution emerges from the analysis. Understanding the seasonal contributions of changes in annual means is highly complex with evidence of different seasons having influences for different parts of the record.

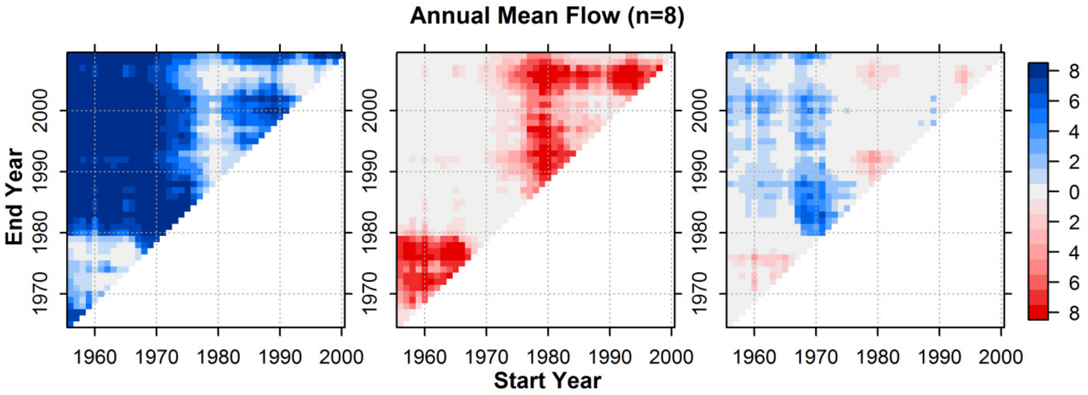


Figure 2: *Moving windows analysis of all possible start and end dates in annual mean flows for 8 long record stations. Left panel shows the number of stations showing increasing trends, the centre panel shows the number of stations showing decreasing trends, while the right panel shows the number of significant trends derived using the Mann-Kendall test. Significance is tested at 5 percent level.*

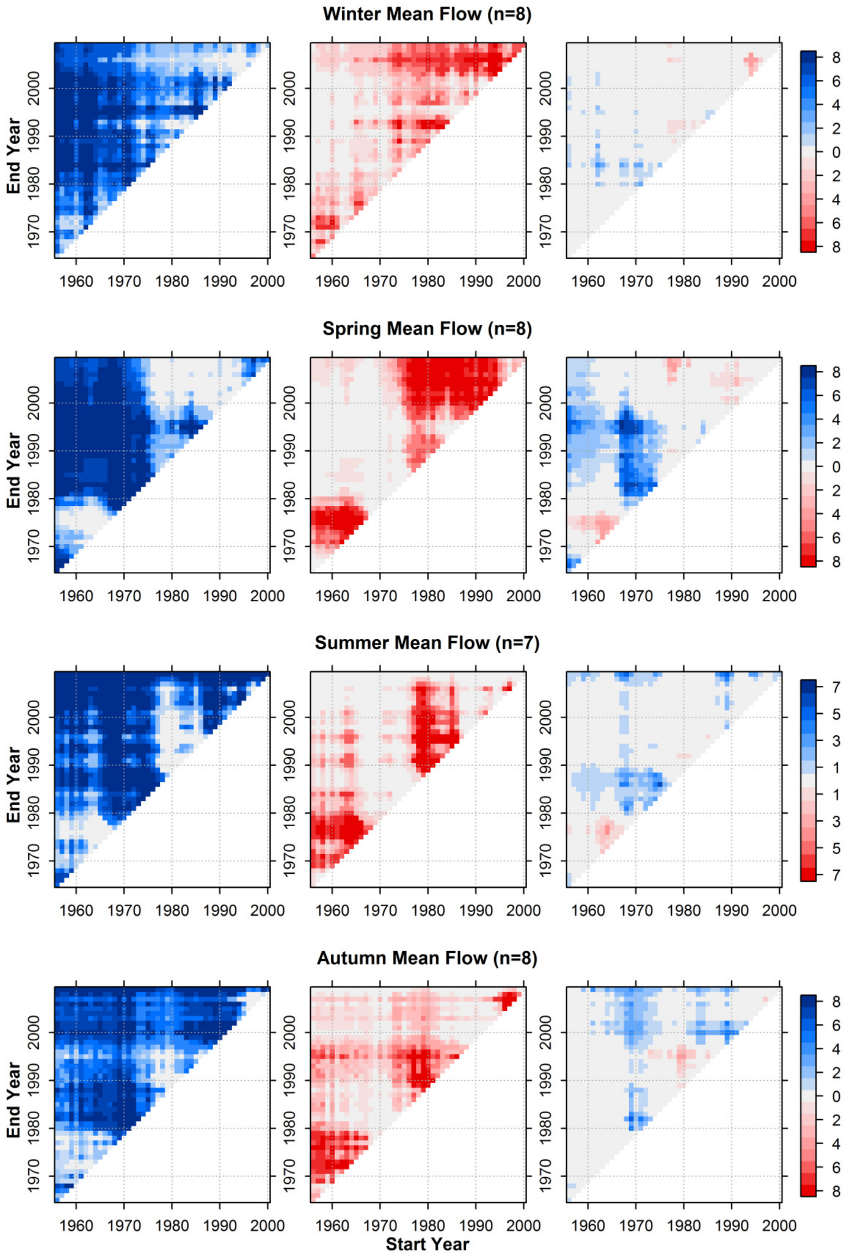
Results for seasonal mean flows are shown in Figure 3. For winter mean flows increases are only found for stations in the west and northwest with decreasing trends in the east and south and particularly strong in the northeast. For longer records (earlier start dates) there is a tendency towards non-significant increasing trends, which are almost significant for the longest records. Decreases in shorter winter records are likely influential in driving decreasing trends in annual means. These shorter record trends are at odds with projected climate change scenarios of wetter winters. However, longer records show a tendency for increasing trends.

In spring, mean flows are dominated by large variability; more than any other season. The record is marked by a period of high spring flows from the mid-1970s to the mid-1990s, after which there is a marked reduction in flows to long term average conditions. Long records show a tendency for strong and significant increasing trends. In recent decades there is a strong transition to decreasing trends especially in the south and southeast.

For shorter records summer mean flows are dominated by increasing trends, some of which are significant. Recent wet summers have had a large influence, especially in determining the statistical significance of these trends. However, even when recent wet summers are removed from the analysis increasing trends remain prevalent. The historical development of the network has also confounded the analysis of summer means, with many stations beginning during the early to mid-1970s – a period of marked drought. However, even for long records increasing trends persist. Autumn mean flows are also dominated by increasing trends throughout the record, with the largest trends in eastern and southern regions. Persistent significant and near significant increasing trends are evident for long records in the southeast. The 1970s drought has also had a bearing on trends for autumn mean flows.

4.2 Trends in high flows

High flow indicators (IAMAX and MAX10) are dominated by increasing trends, a high number of which are significant. However, statistically significant trends have only emerged for records ending after circa 2000, even for the longest records (Figure 4). IAMAX (Instantaneous 15min flows) show persistent increasing trends. Larger trends are evident for longer records. For longer records the significance of trends has largely emerged for records ending after 2000. Short records commencing after 1980 reveal no significant trends for IAMAX. Maximum consecutive ten-day flows (MAX-10) show persistent increasing trends in the western half of the country and also in the southeast. Longer records show stronger trends. Long record trends in MAX10 have also become significant since circa 2000.


Winter Mean Flow (n=8)

Spring Mean Flow (n=8)

Summer Mean Flow (n=7)

Autumn Mean Flow (n=8)

Figure 3: *Moving windows analysis of all possible start and end dates in seasonal mean flows for long record stations. Left panel shows the number of stations showing increasing trends, the centre panel shows the number of stations showing decreasing trends, while the right panel shows the number of significant trends derived using the Mann-Kendall test. Significance is tested at 5 percent level.*

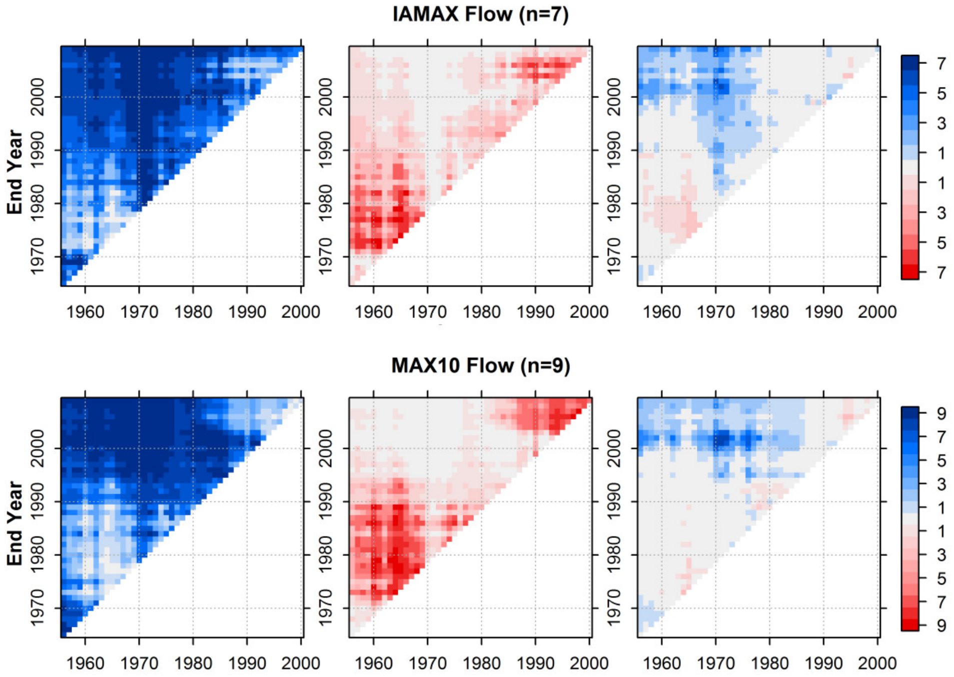


Figure 4: *Moving windows analysis of all possible start and end dates in high flow indicators for long record stations. Left panel shows the number of stations showing increasing trends, the centre panel shows the number of stations showing decreasing trends, while the right panel shows the number of significant trends derived using the Mann-Kendall test. Significance is tested at 5 percent level.*

5. DISCUSSION AND CONCLUSIONS

This research establishes a reference network for monitoring and detecting climate driven trends in Irish river flow records. A network of 43 hydrometric stations, including 8 stations from Northern Ireland (which are part of the UK Benchmark Network) are selected as part of the Irish Reference Network. The flow archive has an average record length of 40 years and draws from the strengths of the existing national hydrometric network. Using criteria based on the quality of flow records and a lack of artificial influences and land-use change, complimented by expert judgement, the Irish Reference Network is a valuable resource facilitating more strategic monitoring of climate driven variability and change in hydrological indicators and enabling more confident attribution of detected trends.

From a strategic and management perspective the identification of stations as part of the IRN enables more focused investment in future monitoring during economically challenging times when emphasis is being placed on rationalising the national hydrometric network. The added utility of climate change monitoring increases the strength of argument that can be made in promoting continued investment in monitoring for these stations, while increasing their efficiency as multi-purpose sites. Formal recognition of the network has been given as part of the recent review of hydrometric stations (EPA, 2011), where climate change monitoring is seen as a primary purpose for the sites identified and used to weight their utility for continued monitoring. In order to capitalise on and ensure the longevity of the IRN, it is important that this recognition is continued and a long term strategy is put in place for the maintenance of these stations. The identification of a network of stations for climate change monitoring and detection should be seen as iterative, and should be updated regularly. This is a first pass. Work in the UK and elsewhere has been ongoing for over ten years in this area. Hydrometric monitoring provides observational evidence for informing policy making and raw data for science and engineering and is vital in an era of change. It is crucial that investment is maintained in this area so as to ensure the continued collection and processing of data to meet the basic information needs for water resource and flood management and environmental reporting. Long records of observations are vital for contextualising trends from shorter series. In the IRN there are a number of long records, however they are not well distributed throughout the country. These long records should be protected. The availability of longer term precipitation data is important for checking consistency of river flows with key drivers and for the extension of flow records to supplement longer flow records.

Strong similarities in the temporal development of trends in each indicator for stations across the network add confidence that trends are climate driven and that the IRN is fit for purpose. The close correspondence of trends in seasonal mean flows with seasonal rainfall totals add to this, while the very similar results obtained from the UK Benchmark Network, analysed using similar methods, point to trends being driven by a common, external and regional scale driver. Trends in Irish river flows are strongly correlated with the winter North Atlantic Oscillation Index (NAOI). As highlighted in previous research (Kiely, 1999) changes in the NAOI have been linked with changes in Irish hydro-climatic variables. A shift towards more negative winter NAOI anomalies since the mid-1990s is also reflected in Irish river flows, particularly for spring mean and high flows. The sensitivity and response of the NAO to greenhouse gas forcing will have obvious implications for Irish hydrology; however the question remains open as to the impact that greenhouse gas forcing has had on recent behaviour of the NAO and how it is likely to respond to future forcing. In addition, Global Climate Models have problems in capturing the observed behaviour of the NAO. Future research in Ireland should explore the influence of other large-scale atmospheric drivers that have been shown to be influential to hydro-climatic conditions than the NAO solely.

While there is considerable evidence of change in the IRN, it is difficult at this point in time to attribute these to anthropogenic greenhouse gas induced climate change. Indeed some of the trends identified – decreases in shorter records in winter mean flows and increases in summer and low flows – are not consistent with expected changes as simulated by Global Climate Models (Murphy *et al.,* 2013b). This should not be surprising given the large variability of river flows relative to climate change signals at this point. Similar disparities have also been highlighted by other research (e.g. Svensson *et al*., 2005, Wilby, 2006; Hannaford and Marsh, 2008). Continued monitoring and analysis of hydro-climatic indicators in future can help reconcile the disparities between observed and projected changes. Of particular interest are the recent findings of Sutton and Dong (2012), which show that warming of North Atlantic sea surface temperatures are associated with wetter summers in Western Europe. This work highlights that the transition from a cool (1960s) to a warm (1990s+) phase of SSTs could account for the unexpected (but perhaps temporary) wetting of summers contrary to long-term climate model projections. Research on more fully attributing changes in the IRN to drivers beyond the NAOI should be a priority.

There is high potential for identifying sentinel stations and indicators within the IRN that can be used for early detection of climate change signals in streamflow records. Early detection is a function of the variance of the observations combined with the strength of trend (future magnitude of change) expected for individual indicators. The detection of signals of change is most difficult for seasonal mean flows – especially summer, given the large amounts of inter-annual variability in these indicators. Trends in seasonal and annual mean flows are unlikely to be statistically detected before mid-century using conservative statistical criteria.

For detecting climate change it may be prudent that a distinction is made between practical and statistical significance, even where trends have not been deemed statistically significant at conservative significance levels (e.g. 5 percent level), they may have profound effects on vulnerable water resources or communities exposed to flood risk. For the foreseeable future, water managers will have to make climate change adaptation decisions in advance of formally detected changes. Robust approaches to adaptation that are based on minimising current vulnerability to climate change and the stress-testing of decisions against the range of possible impacts have been highlighted in the literature and offer considerable potential (e.g. Hall and Murphy, 2011). The development of techniques to detect signals from hydro-climatic time series with high variability is of particular priority for water resource management and research given the difficulties with detecting changes in highly variable low flow indicators with current methods.

Evidence for anthropogenic climate change is unequivocal at the global scale and in temperature records in particular. Recent studies have also pointed to the enhanced probabilities of extreme events, such as the 2009 floods in the UK as a result of greenhouse gas forcing (e.g. Pall *et al.,* 2011). Despite advances in event attribution it remains a challenging task to identify anthropogenic climate change signals in trends at the scales relevant for water management due to a low signal to noise ratio at this point in time. These findings heighten the importance of Reference Hydrometric Networks for monitoring and detecting climate change signals at the catchment scale, for tracking the emergence of signals relative to natural variability and for providing information, free from confounding factors, for validating output from climate change impact assessments and developing adaptation policies.

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