Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

Climate Change Research Programme (CCRP) 2007-2013
Report Series No. 27

HydroDetect

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

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EPA STRIVE Programme 2007-2013

HydroDetect

The Identification and Assessment of Climate Change Indicators
for an Irish Reference Network of River Flow Stations

(2010-CCRP-DS-2.2)

CCRP REPORT

Prepared for the Environmental Protection Agency

by

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ACKNOWLEDGEMENTS

This report is published as part of the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme 2007–2013. The programme is financed by the Irish Government under the National Development Plan 2007–2013. It is administered on behalf of the Department of the Environment, Community and Local Government by the Environment Protection Agency which has the statutory function of co-ordinating and promoting environmental research.

The authors thank the late Micheal MacCárthaigh (Environmental Protection Agency) and Peter Newport (Office of Public Works) for their advice and knowledge in selecting stations for inclusion in the Irish Reference Network). We also thank Noel Higginson (River Agency NI) and Met Éireann for provision of data. In particular, we thank Jamie Hannaford of the UK National River Flow Archive at CEH Wallingford for his generous advice and insights throughout. We also thank Satish Bastola, Colin Holman and Simon Noone for their assistance.

EPA STRIVE PROGRAMME 2007-2013

Published by the Environmental protection Agency, Ireland

PRINTED ON RECYCLED PAPER

ISBN: 978-1-84095-507-1 07/13/150

Price: Free

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Micheál MacCárthaigh 1953–2012

The authors and the EPA wish to dedicate this report to the memory of our esteemed colleague, Micheál MacCartháigh. As was typical of the man, Micheál gave generously of his time and expertise to young researchers engaged on this project. He ensured the research described in this report was of the highest calibre and we benefited enormously from his wealth of knowledge.

Micheál devoted his working life to the collection, analysis and provision of hydrometric data. His contribution has benefited this country and his legacy will benefit future generations, especially in enabling a new generation of researchers to begin planning for the impacts of climate change.

Micheál understood the vital role of reliable, long-term river-level and flow data and associated statistics to enable the wise use and protection of Ireland's water resources. His presence and contribution will be greatly missed in the EPA and the wider water-research community.

Ar dheis Dé go raibh a anam.

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Executive Summary

This research establishes a reference network for monitoring and detecting climate-driven trends in Irish river flow records. A network of 35 hydrometric stations is selected as part of the Irish Reference Network (IRN). The flow archive has an average record length of 40 years and draws from the strengths of the existing national hydrometric network. Using selection criteria based on the quality of flow records and minimisation of artificial influences and land-use change, complemented by expert judgement, the IRN is a valuable resource. It facilitates more strategic monitoring of climate-driven variability and change in hydrological indicators, and enables more confident attribution of detected trends. In furthering the utility and development of the IRN, a number of recommendations can be distilled:

- Hydrometric monitoring, which is vital in an era of change, provides raw data for science and observational evidence for informing policy. It is crucial that investment is maintained in this area to ensure the continued collection and processing of data to meet basic information needs;
- Long records of observations are vital for contextualising shorter series. The IRN contains a number of long records and these should be strongly protected. In regions where long records are not available, the reconstruction of river flows offers a viable avenue to supplementing the observed knowledge on climate variability and change;
- Missing data can be problematic for time series analysis and detection of change. Effort should be made to reduce the amount of missing data in future monitoring and to adopt a formal approach for infilling missing data that is recognised by hydrometric agencies in Ireland;
- The quality of reference networks is founded on the availability and quality of metadata. Different ranking categories are used by different hydrometric agencies, making it difficult to compare quality ratings directly. In addition, information on abstractions and discharges, and information on river-engineering works, needs to be made more readily available to data-users.

Formal recognition of the IRN 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 add justification for their continued monitoring. In order to ensure the longevity of the IRN it is crucial that this recognition is continued.

Analysis of Climate-driven Trends from the Irish Reference Network

An in-depth analysis of trends in 22 indicators of river flow describing the full range of flows was conducted for stations in the IRN, with the spatial distribution of trends across the network examined for the period 1976–2009. For all-island coverage eight Northern Ireland (NI) stations from the UK Hydrometric Benchmark Network are included. To shed light on the temporal development of trends their persistence over longer time periods for varying start dates and the variability of trends for all possible start and end dates are examined. The following key findings emerge:

- For winter mean flows decreasing trends are found for all stations outside of the west and northwest for the 1976–2009 period. The trends obtained from shorter records, which are reflective of record length for most stations in the IRN, are not consistent with climate change scenarios of wetter winters. However, there is a tendency for non-significant increases in winter mean flow for longest record stations;
- Spring mean flows are dominated by natural variability. The records show an increase in spring mean flows from the mid-1970s, consistent with the change point identified by Kiely (1999), which persists up to the mid-1990s, after which there is a considerable reduction in flows relative to this. This is evidenced in the trends derived, with long records showing strong increasing trends in spring mean flows: however, shorter records show a large transition towards decreasing trends, especially in the south and southeast;

- Summer mean flows are dominated by increasing trends, some of which are statistically significant. Extremes at the start (mid-1970s drought) and end (recent wet summers) have had a large influence on trends. However, even when end-of-record extremes are removed, increasing trends still dominate, while even the longest records show a dearth of persistent decreasing trends;
- High flows are dominated by increasing trends for long records, many of which are statistically significant after 2000. Shorter records show considerably fewer significant trends;
- Low flows are heavily influenced by the drought of the mid-1970s, the historical legacy of network expansion at this point in time and exceptionally wet years at the end of record, making it difficult to extract robust trends. For the period 1976–2009 no decreasing trends in the minimum 7-day low flow are found in the IRN, while longer records show no clear direction or patterns in trends.

Attribution of Climate-driven Trends in the Irish Reference Network

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 identified trends – 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. 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 North Atlantic Oscillation (NAO) to greenhouse gas forcing will have obvious implications for Irish hydrology; however, the question remains 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.

Strong similarities in the temporal development of trends 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 adds to this, while the similar results obtained from the UK Benchmark Network point to trends being driven by a common, external and regional-scale driver.

The Potential for Sentinel Stations and Indicators

Evidence for anthropogenic climate change is substantial at the global scale and in temperature records in particular. However, it remains challenging to identify these signals at the catchment scale because of large natural variability and therefore a low signal-to-noise ratio. There is however a high potential for identifying sentinel stations and indicators within the IRN for early detection of climate change signals. Changes in high flows show the greatest potential for early detection, while detection is most difficult for seasonal mean flows due to high inter-annual variability. Using current methods and conservative statistical criteria, projected changes from future scenarios in seasonal and annual mean flows are unlikely to be statistically detected before mid-century.

It is prudent that a distinction is made between practical and statistical significance. Even non-significant trends 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 holds considerable potential.

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.

1 Introduction

1.1 Monitoring and Detecting Climate-driven Trends in River Flows

There is considerable evidence that anthropogenic changes in climate due to increases in greenhouse gases have had a direct effect on the observed global water cycle since the middle of the twentieth century (Gedney *et al*., 2006; Huntington, 2006; IPCC, 2007; Barnett *et al*., 2008). This includes increasing patterns of annual runoff in some regions at higher latitudes (Milly *et al*., 2005), changes to extremes of heavy precipitation (Groisman *et al*., 1999) and an increased frequency of great floods (Milly *et al*., 2005) and drought (Dai *et al*., 2004).

Detection of climate-driven trends at regional scales is more problematic due to high inter-annual and decadal variability of river flows (Burn and Hag Elnur, 2002; Wilby, 2006; Fowler and Wilby, 2010) and the effects of human intervention in natural catchment systems (Marsh, 2010). Nonetheless, early detection of changing water resources and extreme events due to climate change is essential for minimising adverse environmental and societal impacts at basin scales (Ziegler *et al*., 2005), and informing adaptation responses that will need to be founded on a more sophisticated understanding of the likely timing and manifestation of climate change at river-basin scales.

In Ireland, previous studies have established changes in observed precipitation. Sheridan (2001) analysed trends in Irish rainfall records; accumulations, rain days and wet days were found to show significant increases at many stations in certain months (March) and decreases in others (July, August, September). McElwain and Sweeney (2007) found increases in annual rainfall from 1960 in the north and west while decreases or slight increases were evident for the south and east. Extreme rainfall events have become more common in Ireland since 1975 and have been correlated with an increase in the positive phase of the North Atlantic Oscillation (NAO) (Kiely, 1999). Additionally, Kiely *et al.* (2010) highlight that change points in annual total precipitation occurred for synoptic stations near the west coast, marked by a transition to increased rainfall levels around 1975–78. Similar change points are evident in hydrometric records for the Suir, Nore and Fergus rivers with increases in annual and monthly (March and October) means coinciding with increases in precipitation over the latter quarter of the twentieth century. While change points related to natural variability have been detected, no underlying long-term monotonic trends associated with climate change have been unearthed. This has also been the case for the USA (Ziegler *et al*., 2005), Canada (Burn and Hag Elnur, 2002) and the UK (Robson *et al*., 1998; Wilby, 2006).

In contrast, projections of future Irish river flows for the coming century based on a range of global climate models, greenhouse gas emission scenarios, different regionalisation approaches and multiple rainfall-runoff models, project increases in winter flows and reductions in summer flows along with an increase in the magnitude and frequency of extreme events of flooding and drought (Murphy and Charlton, 2008; McGrath *et al.,* 2008; Bastola *et al.,* 2011a; 2011b). Although uncertainties associated with ensembles of future change are large, the associated changes may have substantial implications for sustainable resource management and effective defence from floods and droughts. Additionally, timely delivery of targets as part of European legislation such as the Water Framework Directive (Directive 2000/60/EC) and the Floods Directive (Directive 2007/60/EC) may be challenged. The risks posed by climate change have been highlighted by recent extremes such as the 2009 floods, which resulted in widespread calls for increased investment in, and more effective defence from, flood events.

Observational evidence plays a vital role in addressing these uncertainties and achieving a fuller reconciliation between model-based scenarios and ground truth (Hannaford and Marsh, 2006). At face value, potential mismatches between observed trends and projected changes, especially for the near-term future, could present considerable difficulties for policy-making (Brazdil *et al.,* 2006): however, Wilby (2006) highlights that this can be reconciled by more sophisticated approaches to climate change detection and attribution when using river flow records. Hydrological monitoring programmes have an essential role to play in acquiring the hydrological data necessary to characterise variability and discern any emerging trends, while the identification and interpretation of these trends is a necessary foundation for the development of appropriate water-policy and management responses to climate-driven changes (Hannaford and Marsh, 2006).

As noted by Kundzewicz and Robson (2004), data are the backbone of any attempt to detect trends or other change in hydrological records, with the identification of appropriate sites and quality-assurance procedures essential for meaningful statistical analysis. Additionally, a major problem in relation to the interpretation of trends, particularly in low flows, is the impact of water abstractions on natural flow regimes. Internationally, countries are beginning to capitalise on networks of undisturbed, natural catchments. This task is challenging for Ireland because of the high degree of heterogeneity in catchment geology, land-use, climate, arterial drainage and peat extraction. There is therefore a pressing requirement to capitalise on the existing network to identify reference hydrometric stations representing high-quality records with good rating curves, non-impacted flow regimes, long records, that represent a range of physical settings that can be used for monitoring climate-driven change in Ireland.

1.2 Aims and Objectives

With these priorities and challenges in mind, the overarching aims and objectives of this work are to:

1. Identify a reference network of hydrometric stations that build on the current network of hydrometric stations which can be used to monitor and detect climate-driven changes in river flows;
2. Select and extract a comprehensive set of hydrological indicators that represent the full range of river flow conditions for detection of climate change signals from river flow records;
3. Analyse trends in selected indicators using statistical techniques to explore how climate-driven trends have evolved in flow records for stations in the reference network;
4. Examine the detectability of anthropogenic climate change signals in Irish river flow records;
5. Identify sentinel stations within the network and ‘early-bird’ indicators that are likely to show the earliest statistical detection of anthropogenic climate change signals;
6. Reconstruct river flows to salvage continuous time series for high-quality stations with long records that have been heavily impacted by land-use change, or contain ‘broken records’ due to large amounts of missing data.

The successful delivery of these aims and objectives will facilitate a fuller understanding of climate-driven changes in Irish river flows, increase confidence associated with the attribution of trends and allow strategic and focused investment in monitoring for evidence-based policy development for responding to climate change.

1.3 Legislative Drivers and International Commitments

A key commitment of parties to the Global Climate Observing System (GCOS), of which Ireland is one, is the provision of the sustained global observations required by the World Climate Research Programme (WCRP) and the Intergovernmental Panel on Climate Change (IPCC). Objectives of GCOS developed jointly by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU) include: monitoring the climate system; detecting and attributing climate change; assessing the impacts of, and supporting adaptation to, climate variability; and change and research to improve understanding and modelling and the prediction of the climate system.

The *Progress Report on the Implementation of the Global Observing System for Climate in support of the UNFCCC 2004–2008* (WMO, 2009) identifies a number of important priorities: GCOS is to be further developed to serve optimally the evolving needs of the United Nations Framework Convention on Climate Change (UNFCCC), including immediate attention to the design and implementation of the national and local-scale networks needed for impact assessment and adaptation to climate change; and further development and promulgation of observational standards for the full range of terrestrial-climate variables.

The research conducted here speaks to each of these objectives through the identification of a specialised hydrometric network for monitoring and exploring climate-driven trends in Irish catchments, the identification of hydrometric indicators and their subsequent analysis, the interpretation and assessment of robustness of trends, and the identification of catchment types and indicators which are likely to show early detection of climate change signals.

This work also seeks to meet Irish research objectives. The National Climate Change Strategy (2007–2012) highlights the need for improved understanding of climate change impacts on Ireland and adaptation needs and the development of observations and analysis systems. In terms of the former, the analysis presented allows for improved understanding of the manifestation of climate change within the hydrological system. Furthermore, the National Adaptation Strategy, currently being prepared by government, will provide a framework for the integration of adaptation issues into decision-making at national and local levels. In many circumstances stakeholders will want real-world evidence before investing in adaptation, and any mismatch between observations and future projections may lead to difficulties in decision-making. This work aims to examine the evidence for change in observations and to reconcile any divergences that may emerge. Finally, this research is also closely aligned to the aims of the Science, Technology, Research and Innovation for the Environment (STRIVE) programme 2007–2013, notably through the development of methods and systems for measuring, recording and predicting the environment and the integration of environmental considerations into policies and programmes.

1.4 Structure of Report

In meeting the core research objectives, the report is organised as follows, with sections closely related to each objective. Section 2 details the identification of an IRN of hydrometric river flow gauges for monitoring and detecting climate-driven trends. Background on the utility, benefit and international experience with the establishment and maintenance of national reference hydrometric networks is provided. Key criteria for the selection of stations in the IRN are discussed. Section 2 concludes with a critical appraisal of the IRN and distils some recommendations and future directions for the network.

Section 3 provides a comprehensive analysis of trends in selected indicators representing the full range of river flow regimes for stations across the IRN. It outlines the study design and statistical techniques and presents key results. Owing to complexities in the evolution and interpretation of trends, the analysis presents a number of novel approaches that go beyond commonly used fixed periods of analysis. Effort – albeit a first pass – is also given to attributing the derived trends to likely drivers.

Section 4 considers the catchments and indicators in the IRN that are likely to act as sentinel stations/indicators, by providing the earliest detection of climate change signals for different variables. Consideration is also given to the detectability of anthropogenic climate change signals in mean flows and the amount of change in flows required to be detected at given future time periods.

Section 5 concentrates on the reconstruction of river flow series from long river flow records that are either altered by land-use change or contain too much missing data for inclusion within the IRN. The approach taken to reconstruction is outlined and results are presented in the context of the analysis of Section 3. Finally, the potential for further work on reconstruction is highlighted.

Section 6 provides a summary of results from the entire body of work, draws overall conclusions and makes recommendations for the maintenance and use of the IRN, and recommendations for policy development on adaptation.

2 Identification of a Reference Network of Hydrometric Stations for Climate Change Monitoring and Detection

2.1 Introduction

River flow data have a range of societal benefits and are the foundation of effective water-resource management, providing basic information for resource assessments, regulation and policy development. In the context of changing climatic conditions observations have a key role to play in understanding variability, the detection and attribution of emerging climate change signals, along with the validation of climate change scenarios and the provision of reliable information for training models that generate future predictions. For such purposes, high-quality data from time series that span the time period of interest are required. Reference hydrometric networks, specifically selected for such purposes, are increasingly used internationally.

This section outlines the identification of a reference network of monitoring stations with the specific purpose of monitoring and detecting climate change signals. The section is organised as follows. Section 2.2 provides background on the development of reference hydrometric networks internationally, Section 2.3 provides a discussion around key selection criteria employed in selecting stations. Section 2.4 provides an introduction to hydrometric monitoring in Ireland, focusing particularly on the roles of national agencies and on key moments in the expansion of the network. In Section 2.5 the criteria for selection of stations for inclusion in the IRN are outlined and the network is introduced. The section ends with a critical appraisal of the identified network and the identification of outstanding priorities and recommendations for future actions.

2.2 Reference Hydrometric Networks

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), including the UK, the USA and Canada (Whitfield *et al*., 2012), 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 valuable data source to identify, quantify and interpret hydrological change effectively, the speed and magnitude of which is expected to be a principle driver of water-management and flood-alleviation strategies through the twenty-first century (Marsh, 2010).

In North America, Slack and Landwehr (1992) reviewed all United States Geological Survey (USGS) river flow recording sites as part of the Hydro-Climatic Data Network (HCDN). For Canada Harvey *et al*. (1999) developed a series of criteria and applied them systematically to sites within their national hydrometric network to identify a network of around 200 stations with relatively pristine and stable land-use conditions, termed the Reference Hydrometric Basin Network (RHBN). These data have been employed in many trend-detection studies in both North America (Lins and Slack, 1999; Douglas *et al*., 2000; Zhang *et al*., 2001) and Canada (Burn and Hag Elnur, 2002; Ehsanzadeh and Adamowski, 2010; Burn *et al*., 2012).

Internationally, the utility of such reference networks for identifying, quantifying and interpreting hydrological change across a range of scales from the catchment to international comparisons is being increasingly appreciated (Whitfield *et al*., 2012). While data requirements can be demanding, RHNs provide a more reliable basis for detecting climate variability and change (e.g., Lins and Slack, 1999; Douglas *et al*., 2000; Zhang *et al*., 2001; Adamowski and Bocci, 2001; Burn and Hag Elnur, 2002; Yue and Wang, 2002; Hannaford and Marsh, 2006, 2008). 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 contextualising trends from recent decades.

2.3 Summary of Criteria for Identification of Reference Networks

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). In terms of basin development reference stations should ideally be pristine or have stable land-use for the period of record included. The objective of river flow monitoring is to capture the output from a complex and dynamic natural system and is therefore a challenging task. Large flood events or continuous erosion over time can alter the cross-section of rivers, affecting flow ratings while seasonal weed growth can affect flow ratings during low-flow and drought conditions. River regulation can include diversions, impoundments, abstractions and changes to channel morphology. Obviously, such confounding factors can influence different parts of the flow regime of a catchment heavily and limit the ability to characterise the natural variability of flow and significantly hamper the detection of climate change signals. Given the pervasive impacts that human activities have had on natural catchment conditions over the past century it is particularly difficult to identify stations that are truly pristine or entirely without some degree of regulation. Therefore, as Whitfield *et al.* (2012) highlight, emphasis must be placed on capitalising effectively on the existing hydrometric network.

Consequently, in realising the full potential of existing hydrometric networks, compromises are often necessary for the inclusion of representative catchment types and to ensure adequate spatial coverage. What constitutes 'near-natural' conditions is highly 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 '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 (flow exceeded 95 percent of the time) exceedance threshold (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 long-term 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).

2.4 The Irish Hydrometric Network

Ireland's rich history of hydrometric monitoring has resulted in a network of over 800 currently active hydrometric-gauging stations (EPA, 2012), with good spatial coverage, in some cases dating back to the 1940s. However, the priorities for hydrometric monitoring in the past have not included climate change and have been driven by factors such as monitoring of arterial drainage works, electricity generation, infrastructural development and warning and control of extreme events (MacCárthaigh, 1995).

Two national agencies, the Environmental Protection Agency (EPA) and the Office of Public Works (OPW) have remits relating to the collection and provision of hydrometric data. The EPA collects, collates and distributes hydrometric data from gauges owned and maintained by local authorities (LAs) and also has an advisory capacity in the development of LA river flow networks. A key moment in the development of the EPA–LA network in particular was the 1976 drought that was experienced widely in Ireland and the UK and highlighted the need for closer monitoring of river flows, particularly low flows for the purposes of water provision. In addition, the passing of the Local Government (Water Pollution) Act in 1977 placed responsibility for the monitoring, management and control of quality in water bodies with LAs (MacCárthaigh, 2002). Such responsibility saw a considerable expansion in the density and spatial coverage of the hydrometric network in the 1970s (MacCárthaigh, pers comm.).

While the major objective of the EPA–LA network is the monitoring of low flows, the OPW's remit is largely in the area of flood-risk management. The key purpose of these stations has been for monitoring floods and arterial drainage and for providing data for flood early-warning systems. While stations in the OPW network generally have longer records than the EPA–LA, many have been adversely affected by the impacts of arterial drainage (see Section 5.3.1), which included the widening and deepening of river channels.

This shared responsibility has resulted in two hydrometric networks being operated and maintained by separate agencies. According to a recent review of the EPA hydrometric network (EPA, 2011) there are 262 hydrometric stations in the EPA–LA network where continuous water-level recording is taking place, with flow data derived from 232 of these stations. The OPW network has 379 hydrometric stations where continuous water-level recording is taking place, with flow data derived from 245 of these. Such historical and institutional diversity in the development of the Irish hydrometric network means that there is a pressing requirement to capitalise on the existing network to identify a benchmark or reference network of river flow gauges that can be used for monitoring climate-driven changes in hydrometric records in Ireland.

2.5 The Irish Reference Network for Monitoring and Detecting Climate-driven Hydrological Change

The overarching aim of this work is to identify a sub-set of river flow gauges from the broader hydrometric register of gauges for monitoring and detecting climate-driven hydrological change. More specifically, this sub-set of stations should meet acceptable quality assurance, have sufficiently long records for monitoring and detecting climate-driven hydrological change, while also providing a good representation of the varied hydrological characteristics of the island. Following an extensive review of the literature and taking account of available metadata in Ireland, key criteria for the selection of gauges for inclusion in the IRN are outlined below and further expanded upon in subsequent paragraphs. The following are key selection criteria for inclusion in the IRN:

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 eight Water Framework Directive (WFD) River Basin Districts (RBDs) covering the island are included;
6. Consultation with principal hydrometric agencies, including the EPA and the 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 (NRFA) at the Centre for Ecology and Hydrology (CEH).

Hydrometric rating quality was assessed using the quality categories employed by each hydrometric agency to examine the prevalence of good-quality flow measurements throughout each individual flow series. One confounding factor identified in this process was the different rating categories used by each agency, making it difficult to directly compare quality codes between OPW and EPA–LA stations. In addition, use was made of the ratings given to hydrometric stations as part of the OPW Flood Studied Update (FSU) for Ireland. This study gave each station a rating based on its ability to accurately capture high flows and categorised stations into A1, A2, B and C classes. Preference was given to stations with A1 and A2 categories. Finally, in order to determine the quality and stability of flow ratings expert advice was obtained from responsible personnel in the hydrometric divisions of both the EPA and OPW. In addition to verbal consultation 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 presented above to be relaxed in order to better capitalise 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. The different objectives of the EPA–LA and OPW also have an influence here. To ensure that good-quality data were used to extract hydrological indicators for trend analysis, plots of data quality were produced and examined. (Details on the extraction and use of indicators are given in Section 3.) Figure 2.1 gives an example of the specific indicator plots produced, in this case for the MAX10 flow indicator which is a high-flow measure (see Section 3). 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. For the stations selected Appendix 1 provides details on the indicators analysed for each station.

In order to ensure that stations were not overly influenced by abstractions and discharges expert consultation was obtained. 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 Smith (2009). Rather than omit stations with abstractions, stations were identified as near natural where the net impact of abstractions and discharges were within 10 percent of the natural flow at, or in excess of, Q95. These criteria have also been used in the UK Benchmark Network (Bradford and Marsh, 2003; Hannaford and Marsh, 2008).

The historical development of the hydrometric network in Ireland, as discussed above, has a large bearing on the average length of record achievable. Therefore, careful consideration was given to identifying and including stations with longer records. A record length of 25 years was identified as a minimum for inclusion in the IRN. In terms of land-use, only stations with an urban extent of less than 2.5 percent of the catchment area were included due to the confounding issues that urbanisation can have on trend detection. In identifying

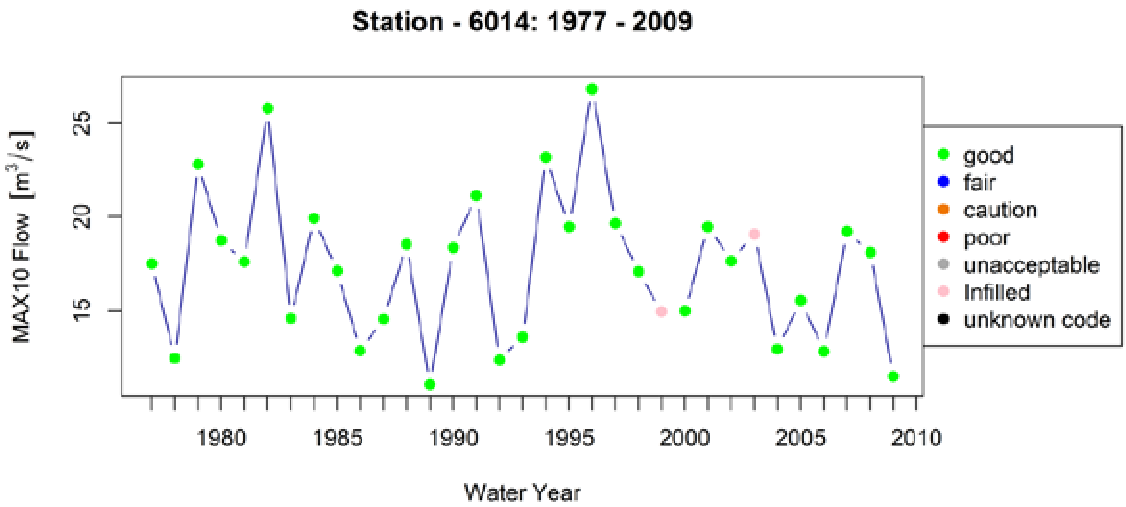

Figure 2.1. Example of an indicator (MAX10) specific quality plot produced to check the quality of data used in extracting indicators for trend analysis from individual stations. The plot shows the maximum 10-day flows for each year for the specific station. In this case, the dominant quality category over the 10 days was assigned.

urban extent the URBEXT (percent of catchment covered by urban area) catchment descriptor from the OPW Flood Studies Update (FSU) was employed.

The biggest confounding factor in identifying stations in Ireland was 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 RBDs. In addition, stations from Northern Ireland that are part of the UK Benchmark Network were also included to ensure all-island coverage.

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. Table 2.1 provides summary details of all the stations selected for the IRN, including the UK Benchmark stations used in the analysis. These are also mapped in Fig. 2.2. A full list of stations in the network and more detailed notes are available in Appendix 1.

2.6 Irish Reference Network Appraisal and Future Directions

This study marks the first attempt to identify a network of river flow stations in Ireland that can be used for monitoring and detecting climate-driven trends in hydrological indicators. Through limiting confounding factors and identifying high-quality data such a network is a valuable tool for increasing confidence in trends identified and facilitates increased rigour in the attribution of drivers of change. The development of the IRN has capitalised on the existing hydrometric network and provides a dataset that can be used for investigations of natural variability and non-stationarity in records, anthropogenic climate change and for modelling purposes such as training and verifying hydrological models. However, it should be emphasised that users of the dataset should be aware of some limitations associated with the 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 should 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. In the east, one of the best-quality and longest records available – the Boyne at Slane Castle – has been heavily impacted by arterial drainage and therefore only the post-drainage record is included. Additionally, St10002 (the Avonmore at Rathdrum), while providing records back to the 1950s is heavily affected by missing data. Both are high-quality stations and should become a more important part of the network in years to come. In order to extract as much information as possible, both are included for river flow reconstruction (Section 5). In the west of the country many stations considered contained large gaps in the record and/or were recently drained.

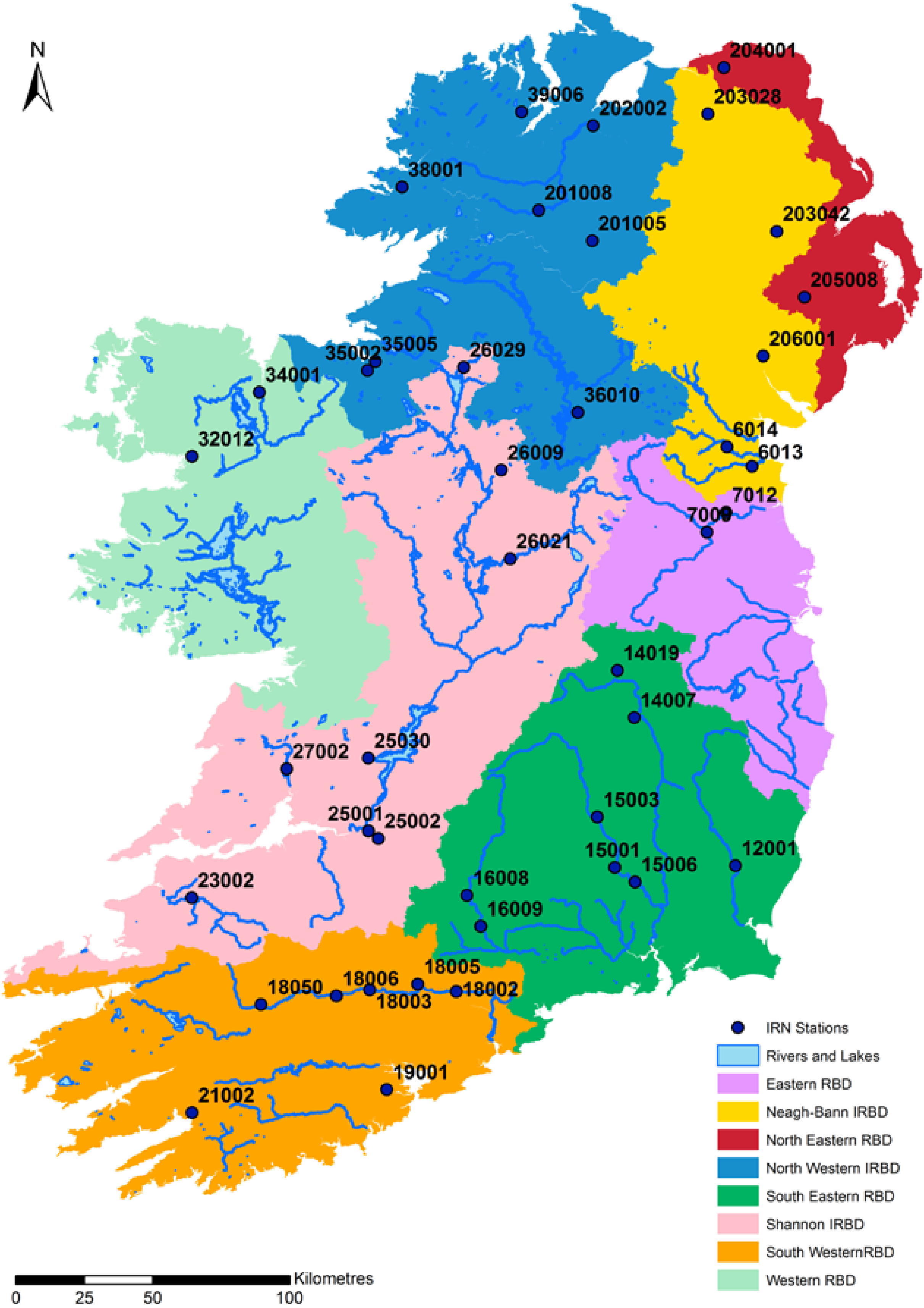

Figure 2.2. Spatial distribution of stations selected as part of the Irish Reference Network (IRN) and the Northern Irish stations in the UK Benchmark Network.

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. It is important that investment in high-quality monitoring is maintained to facilitate inclusion of such sites in the next iteration of the IRN. Overall, the IRN is considered to be broadly representative of Irish hydrological conditions. However, it is recommended that future work could quantitatively assess the representativeness of the network. Such approaches have been developed by Laize (2004) in the UK and would be useful in further detailing network development both of the IRN and the broader hydrometric monitoring network in Ireland, but was outside the scope of this one-year desk study.

A number of 'nested' catchments are evident in the network, particularly in the Blackwater and Suir catchments in the south and southeast. Nested catchments are defined as catchments within which two or more gauges are located. While this is not necessarily an issue, and represents the high quality of sites in these catchments, it is worth noting that there will be a correlation between river flow regimes in these nested catchments. Such correlation means that the same signal may be given greater prominence in overall trend analysis results from the network. Additionally, in comparison to other international reference networks there is a very wide range of catchment sizes in the IRN. This is seen as a relative advantage of the IRN and allows the potential for future work to explore different hydrological responses to climate-driven change at different catchment scales.

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 the 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. Nonetheless, long record stations are not widely distributed throughout the country, with the greatest number of stations located in the southeast. The availability of long-term rainfall records suggests that flow reconstruction using modelling techniques holds a lot of potential for extending shorter IRN stations.

As mentioned above, the availability of good-quality metadata is a key determinant of the quality of the overall network. During the process of selecting stations a number of issues with available metadata were noted. In particular, with the exception of arterial drainage, there is limited data currently available on land-use change. This has been identified as problematic for other RHNs in Europe (Whitfield *et al.*, 2012). In addition, a number of disparities were noted for two separate datasets on surface water abstractions in Ireland where differing volumes for abstractions were found for some abstraction points. While they did not affect the threshold used for characterising near-natural catchments, future work should validate this information.

Missing data is problematic for many hydrometric stations in Ireland. The average amount of missing data is 4.7 percent for the stations selected. However, some stations have considerably more, particularly where stations were identified to meet strategic gaps in the network. Therefore, infilling of gaps was undertaken for the purposes of trend analysis. Section 3 deals with missing data and infilling in more detail; however, it is important to highlight here that a more formal approach should be identified for infilling river flow records in Ireland. We find that the method used in the current research – hydrological modelling – is fit for purpose, but future work in this area, which compares the success and ease of applicability of different infilling methods, should be a priority.

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. 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

Table 2.1. Stations identified as part of the Irish Reference Network (IRN) for monitoring and detecting climate-driven change. Years ending 2009 represent the number of years included in the analysis of trends in Section 3. See Appendix 1 for full details on stations.

Station	Station name	River name	RBD	Org	Easting	Northing	Area [km^2]	Length years
06013	Charleville Weir	Dee	NB	OPW	304411	290763	309	34
06014	Tallanstown Weir	Glyde	NB	OPW	295298	297888	270	34
07009	Navan Weir	Boyne	E	OPW	287905	266761	1684	33
07012	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

EPA=Environmental Protection Agency; NI=Northern Ireland; OPW=Office of Public Works; Org=Hydrometric Organisation; RBD=River Basin District (NB=Neagh Bann, E=Eastern, SE=Southeastern, SW=Southwestern, SH=Shannon, W=Western, NW=Northwestern).

ensure the longevity of the IRN it is important that this recognition is continued. This is particularly pressing where sites are owned and maintained by LAs who are facing increased financial pressures. The importance of maintaining high-quality observations for informed, evidence-based decision-making should not be lost and LAs from which reference stations have been included (Cork, Cavan, Donegal and Mayo) should be commended for their investment in high-quality hydrometric monitoring.

3 The Analysis of Trends from the Irish Reference Network

3.1 Introduction

This section presents the analysis of trends for each of the stations identified as part of the IRN. For all-island coverage, analysis is also conducted for 8 Northern Ireland stations that are part of the UK Benchmark Network. Commonly used statistical tests – Mann-Kendall and the Theil-Sen approach – were used to investigate trends. The study design was set around three approaches to analysing trends: (i) using a fixed period of analysis, (ii) examination of the persistence of trends, and (iii) a moving windows assessment of all possible start and end dates. First, the traditional fixed period analysis, based on a single time period of interest, selected to optimise the record length versus the spatial distribution of stations, was conducted. 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.

In overcoming these issues, the analysis was extended to examine the evolution of trends over the full period of record for individual stations. In the second approach, the persistence of trends was examined by sequentially dropping the start year of analysis down to a minimum number of years. Plotting the strength of trends for each iteration allowed a fuller understanding of the evolution of trends and also an indication of the persistence of any significant trends throughout the period of record. However, the limit of this second approach is that results of the trend analysis are still dependent on the end of the record, where extremes in one or two years can alter the direction/strength and significance of trends. This is of particular relevance here given the extremely wet sequence of summers occurring in recent years in Ireland.

Finally, in addressing the combined issues of set periods and the persistence approach a 'moving windows' method was employed to assess trends for all possible combinations of start and end years. Such an approach facilitated a more thorough understanding of how the strength and timing of trends in river flow indicators evolved across the country. It also facilitated the identification of directional changes versus more gradual trends that are important for assessing the role of climate forcings.

The presentation of results is laid out as follows: Section 3.2 presents the indicators that were extracted from the IRN archive to examine for evidence of trend. Due to the influential role that missing data can have on trends, the method employed for infilling missing data is described in Section 3.3. Following this, Section 3.4 introduces the statistical methods used for trend detection and significance testing. In Section 3.5, results are presented separately for the three approaches employed. In conclusion a summary of the key findings for each indicator is given and a final discussion aims to establish the drivers of change within the IRN, particularly whether these are climate driven and whether or not anthropogenic climate change can be detected from river flow records at this point in time.

3.2 The Identification of Indicators for Analysis

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, given the pervasive impacts that climate change is likely to have on river flows. Table 3.1 provides a full list of the indicators examined, along with a description of how each was calculated. Together, the indicators represent a comprehensive assessment of the flow regime and are categorised as (i) core (based on the analysis of seasonal and annual mean flows), (ii) seasonal extremes and (iii) high and low-flow extremes. Indicators for monthly mean flows were also extracted and analysed but are not presented because of the space limitations associated with their use.

Table 3.1. Overview of each of the 22 indicators extracted from the IRN archive and analysed for trends.

		Indicator	How to calculate	Description/aim
Core or mean indicators (6)	Mean	AN_Mean	Mean of daily mean flows (Dec to Nov) with the Dec taken from the year before.	Changes in magnitude of annual mean flow over time.
		Seasonal_ Mean	Mean of daily mean flows for each season: W (Dec from year before), SP, SU, A	Changes in magnitude of seasonal mean flow over time.
	Seasonality	SE	Mean of daily mean winter flow divided by mean of daily mean summer flows: winter / summer	Changes in seasonality (ratio of winter to summer flows).
Seasonal extremes (8)	Q10	Seasonal_Q10	Q10 of daily mean flows for each season for each WY: A (from year before), W (Dec from year before), SP, SU	High-flow indicator. Changes in magnitude of seasonal Q10 over time. Q10 is the flow which was equalled or exceeded for 10% of the term.
	Q90	Seasonal_Q90	Q90 of daily mean flows for each season for each CY: W (Dec from year before), SP, SU, A	Low-flow indicator. Changes in magnitude of seasonal Q90 over time. Q90 is the flow which was equalled or exceeded for 90% of the term.
Extremes (8)	Instantaneous	IAMAX	Maximum flow value in each WY from sub-daily 15-minute instantaneous flow data.	Changes in magnitude of instantaneous annual max. flow over time.
		IAMAX _JD	JD in each WY that the 15-minute instantaneous annual max. flow occurred.	Changes in the timing of the annual max. flow (occurrence earlier or later in the year).
	High flow	MAX10	Highest 10-day consecutive daily mean flows in each WY.	Changes in magnitude of the consecutive max. 10-day event over time.
		MAX10_JD	JD in which the max. 10-day flow period begun in each WY.	Changes in the timing of the max. 10-day flow (occurrence earlier or later in the year).
		MAX30	Highest 30-day consecutive daily mean flows in each WY.	Changes in the magnitude of the consecutive max. 30-day event over time.
		MAX30_JD	JD in which the max. 30-day period begun in each WY.	Changes in the timing of the max. 30-day flow (occurrence earlier or later in the year).
	Low flow	MIN7	Lowest 7-day consecutive daily mean flows in each CY.	Changes in the magnitude of the consecutive min. 7-day event over time.
		MIN7_JD	JD in which the minimum 7-day period begun in each CY.	Changes in the timing of the min. 7-day flow (occurrence earlier or later in the year).

A – autumn; CY=Calendar Year; JD=Julian Day; SP – spring; SU – summer; W – winter; WY=Water Year.

All indicators are calculated in m^3s^{-1}, with the exception of seasonality which is a dimensionless ratio and indicators assessing the timing of flows which are based on Julian Day (JD). Indicators for mean flows are based on calendar year and derived from daily mean flow data. Seasons are defined as Winter (DJF – December extracted from previous year), Spring (MAM), Summer (JJA) and Autumn (SON). High-flow indicators are extracted from water years (1 October–30 September) to limit the effects of dependence between high-flow events. IAMAX is derived from instantaneous 15-minute flows and are only analysed, where available, for OPW and Northern Ireland stations.

3.3 Missing Data

Missing data can be problematic for the analysis of trends. Stations within the reference network have on average 4.7 percent missing data (see the IRN station information table in Appendix I for individual station missing data). Therefore, different infilling techniques were considered, particularly the methods identified by Harvey *et al.* (2012), who recommend the identification of donor stations where neighbouring stations are identified to develop regressions with target stations for infilling. For stations in the IRN there were many instances in which the identification of donor stations could not fully account for missing data, especially for long record stations in the network.

In seeking consistency in methodology missing data were infilled using a lumped conceptual rainfall runoff model. The HYSIM model (Manley, 2006), which has been previously applied in Ireland (Charlton *et al*., 2006; Murphy *et al.,* 2006; Hall and Murphy, 2011), was employed. The justification for using HYSIM for infilling was further supported by good performance of the model for reconstructed stations (see Section 5). The model was calibrated and verified for all but three catchments (which had very little missing data) in the IRN, with inputs of catchment precipitation and potential evapotranspiration obtained from Met Éireann. Modelling was conducted on a daily time-step. Therefore, infilling was not conducted for IAMAX, which is derived from 15-minute instantaneous flows.

In all cases, infilled 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 infilled and non-infilled series for all stations in the network. The direction and statistical significance of trends were very similar after infilling compared with unfilled data while minor differences were observed for the strength of trends. Figure 3.1 shows the comparison of Mann-Kendall Zs values for both infilled and non-infilled data for selected indicators that represent the range of flow conditions. Figure 3.2 provides a comparison of infilled and non-infilled monthly flow series for one station. Evident is the similarity of results between the infilled and non-infilled series. With the exception of the IAMAX series all subsequent analysis was based on in-filled series.

3.4 Statistical Methods for Trend Detection

Trend was analysed using two widely applied statistical techniques (see Murphy *et al*., 2013 for further detail).

1 The ***Mann-Kendall (MK) test*** for trend (Kendall, 1975) which is a rank-based, non-parametric test for monotonic 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.

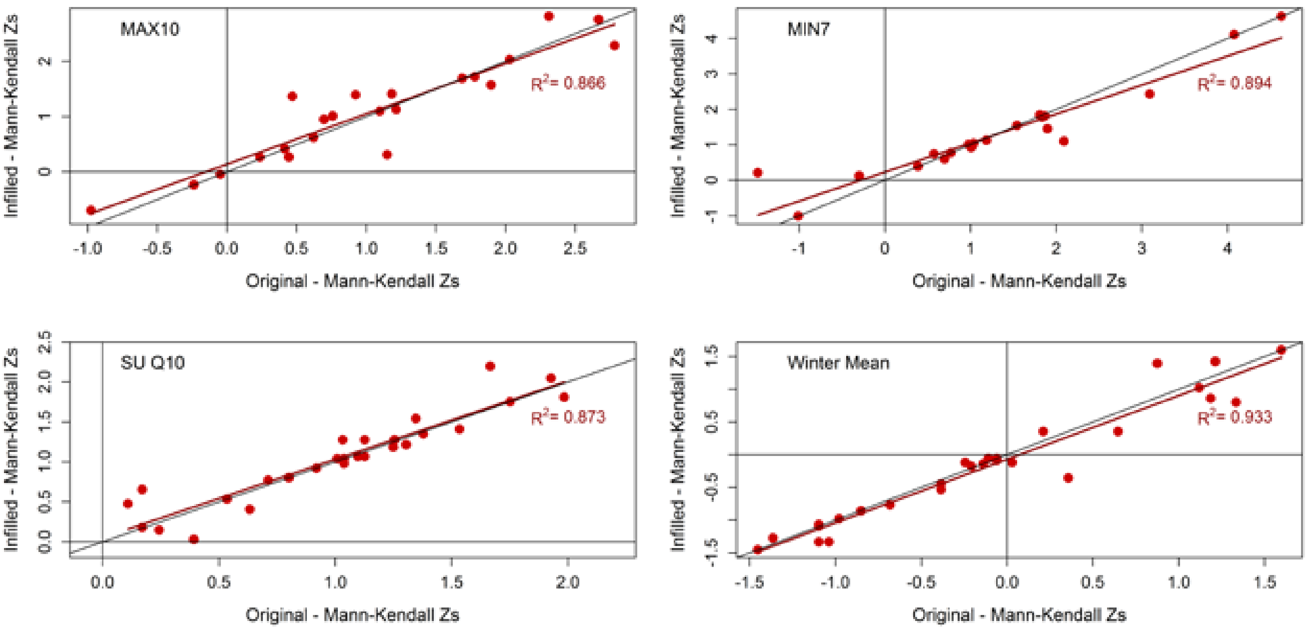

Figure 3.1. Comparison of Mann-Kendall Zs statistic values for infilled and non-infilled time series for selected indicators representing the range of the flow regime. Trends calculated for the period 1976–2009.

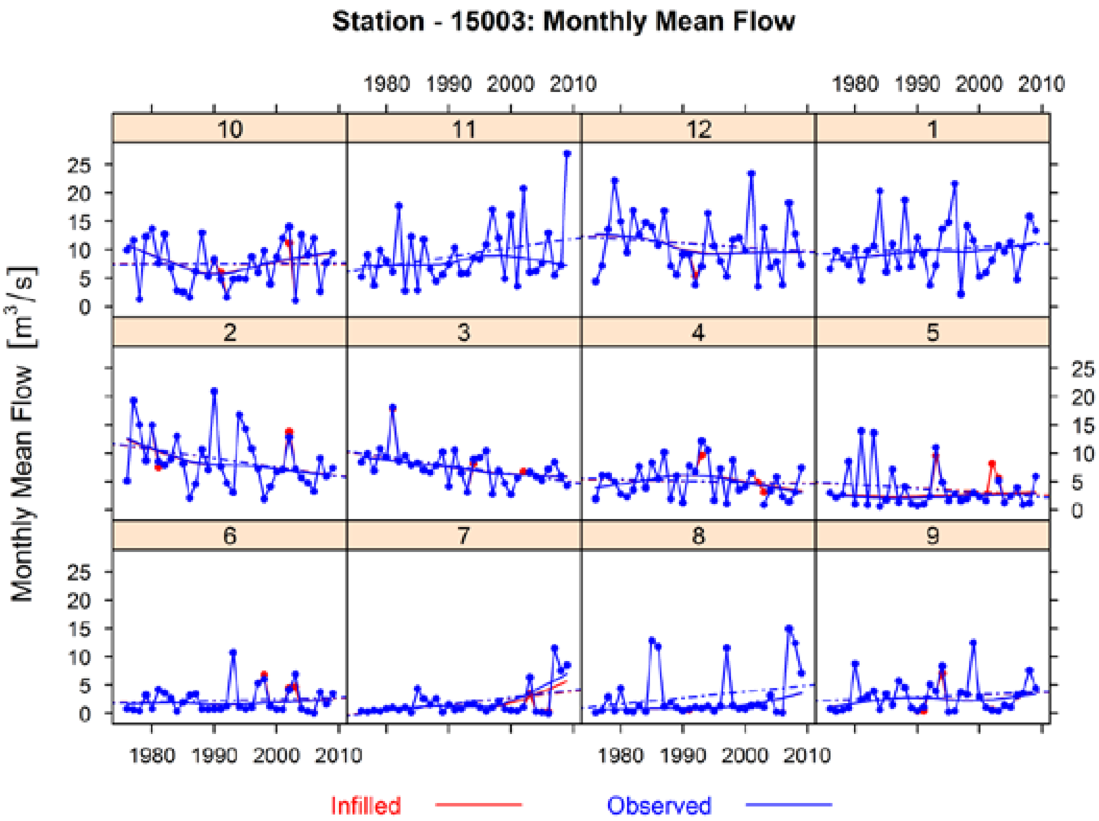

Figure 3.2. Comparison of infilled and observed series for monthly mean flows for station St15003. Months are ordered for water year (WY) beginning October.

2 The ***Theil-Sen approach (TSA)*** (Theil, 1950; Sen, 1968) is a non-parametric test for estimating the slope of trends. The TSA method is comparable to linear regression but is more robust to outliers. TSA was employed for confirming results from the MK test and for comparison of trend magnitudes across stations. TSA slopes were calculated from time series of the standardised river flow after Déry *et al*. (2005) and allow direct comparison of river flow anomalies despite their large range in absolute values. Positive (negative) values indicate above (below) average flow quantities with slopes expressed in standard deviations per year.

In applying trend tests attention was placed on the magnitude and direction of trends over time, in addition to evaluating the statistical significance of results. In evaluating significance, ongoing discussions in the literature regarding the difficulties of statistical testing in hydro-climatic variables were taken into account. Key arguments advanced are based around the difficulties of establishing a valid null hypothesis (no trend) and the impact of long-term persistence on variables used in testing for trend which affect the robustness of findings (see, e.g., Cohn and Lins, 2005; Koutsoyiannis and Montanari, 2007; Clarke, 2010; Stahl *et al.*, 2010).

In this study the statistical significance of trends was evaluated for the MK test only with the probability of Type I error set at 5 percent (5 percent significance level). A two-tailed test was chosen, where the null hypothesis of no trend (increasing or decreasing trend) was rejected if |MK Zs| > 1.96. A number of approaches to statistical testing were taken, including the use of 'normal probability tables' and bootstrap resampling. In catering for the assumption of serial independence in testing, bootstrapping allows any correlation structure in the data to be maintained. Further details on the utility of bootstrapping are given by Kundzewicz and Robson (2000).

3.4.1 Autocorrelation

The Mann-Kendall test is based on the assumption that the data are serially independent. The presence of serial or autocorrelation in a time series is problematic for determining the statistical significance of trends (Hamed and Rao, 1998). The tendency for persistence or consecutive wet or dry years is well known in hydrological data and can result in positive autocorrelation. In such situations the number of false positive outcomes or Type I errors can increase, leading to rejection of the null hypothesis of no trend when the opposite is true (von Storch, 1995).

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 were not unduly affected by autocorrelation. There were indicators however for which some stations show statistically significant (5 percent significance level) positive lag-1 serial correlation. The occurrence of autocorrelation was predominantly associated with low flows including: SU_Mean (16 percent of stations), MIN7 day flow (6.5 percent of stations) and SU_Q90 (11 percent of stations).

In testing the significance of trends for indicators and stations with evidence of autocorrelation block bootstrapping was employed to preserve the correlation structure of the time series. The block length was chosen so that the data points one block apart were approximately independent (see Önöz and Bayazit, 2012). Önöz and Bayazit (2012) highlight that using 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 percent) is L=4 when r≤0.3 and L=4 or 5 when n≤50 (Önöz and Bayazit, 2012). In line with these findings a block length of 4 was used to allow for serial correlation. In the absence of a trend any ordering of the data is equally likely, so if the data fall into the tails of the bootstrap distribution, they are significant. 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 was higher than the 9,750th largest or lower than the 250th MK Zs statistic of 10,000 samples.

3.5 Results – Fixed Period of Analysis

The first part of the analysis explored trends for a fixed period of analysis, selected to optimise the record length versus the spatial distribution of stations. The period selected is 1976–2009 and to incorporate as many stations as possible stations that commence within three years of this period were selected. Table 3.2 gives the results of the analysis for each indicator, and provides the direction and proportion of significant trends. All trends were derived using the MK test with significance determined using statistical tables and block bootstrapping. Where autocorrelation was found to be significant, bootstrapping was conducted with a block length of 4, otherwise a block length of 1 was used. The spatial distribution of trends are mapped and discussed separately for mean flows, high flows and low flows.

From Table 3.2 it is apparent that some indicators show a different percentage of significant trends depending on the method used for significance testing. This was due to the presence of autocorrelation and, when accounted for, fewer stations are statistically significant. However, differences are small and amount to only one station in most instances. Additionally, the direction of trends is identical for both the Mann-Kendall test and the Theil-Sen approach. Comparing all indicators, the highest number of significant trends was found in more extreme indicators, with SU_Q90 revealing significant increasing trends for almost one-quarter of stations. For MIN7 over 90 percent of stations show increasing trends with 16 percent of these significant. SU_Mean flows show an overwhelming dominance of increasing trends with over 97 percent of stations showing increases, 13.5 percent of which are significant. For high flows significant trends are found for over 19 percent of stations for IAMAX and MAX10. With the exception of summer, very few significant trends are found in mean-flow indicators, and surprisingly winter is dominated by decreasing flows for the selected period.

3.5.1 Trends in Mean Flows 1976–2009

Figure 3.3 presents the spatial distribution of trends for seasonal and annual mean flows. For annual mean flows few significant trends emerge. However, there is some spatial variability in results with largest increasing trends located in the west and northwest. Decreasing trends, which are weaker in comparison, are predominant in the south of the country.

For winter mean flows there is a dearth of significant trends, with only one station in the northeast showing a significant (decreasing) trend. In winter there is a spatial

Table 3.2. Percentage of stations showing increasing and decreasing trends and percentage significant trends for all indicators for the period 1976–2009. MK is Mann-Kendall, TSA is the Theil-Sen approach. Significance is only tested for MK using statistical tables and bootstrapping (BS). BS is conducted using a block length of 1 where no autocorrelation is found, otherwise a block length of 4.

		Positive (%)		Negative (%)	
		Total +	Significant	Total -	Significant
ANmean(37 stations)	MK	64.86	2.70	35.14	2.70
	MK BS	64.86	2.70	35.14	2.70
	TSA	64.86	-	35.14	-
WImean(37 stations)	MK	32.43	0.00	67.57	2.70
	MK BS	32.43	0.00	67.57	2.70
	TSA	32.43	-	67.57	-
SPmean(37 stations)	MK	24.32	0.00	75.68	16.22
	MK BS	24.32	0.00	75.68	13.51
	TSA	24.32	-	75.68	-
SUmean(37 stations)	MK	97.30	13.51	2.70	0.00
	MK BS	97.30	13.51	2.70	0.00
	TSA	97.30	-	2.70	-
AUmean (37 stations)	MK	81.08	0.00	18.92	0.00
	MK BS	81.08	0.00	18.92	0.00
	TSA	81.08	-	18.92	-
SE(37 stations)	MK	5.41	0.00	94.59	13.51
	MK BS	5.41	0.00	94.59	13.51
	TSA	5.41	-	94.59	-
SQ10_W(37 stations)	MK	64.86	8.11	35.14	0.00
	MK BS	64.86	10.81	35.14	0.00
	TSA	64.86	-	35.14	-
SQ10_SP (37 stations)	MK	24.32	0.00	75.68	10.81
	MK BS	24.32	0.00	75.68	10.81
	TSA	24.32	-	75.68	-
SQ10_SU (37 stations)	MK	97.30	5.41	2.70	0.00
	MK BS	97.30	8.11	2.70	0.00
	TSA	97.30	-	2.70	-
SQ10_A (37 stations)	MK	75.68	10.81	24.32	2.70
	MK BS	75.68	10.81	24.32	2.70
	TSA	75.68	-	24.32	-
SQ90_W(37 stations)	MK	18.90	0.00	81.10	13.50
	MK BS	18.90	0.00	81.10	10.80
	TSA	18.90	-	81.10	-
SQ90_SP (37 stations)	MK	54.05	8.11	45.95	5.41
	MK BS	54.05	8.11	45.95	5.41
	TSA	54.05	-	45.95	-
SQ90_SU (37 stations)	MK	89.19	24.32	10.81	2.70
	MK BS	89.19	21.62	10.81	2.70
	TSA	89.19	-	10.81	-
SQ90_A (37 stations)	MK	78.38	8.11	21.62	2.70
	MK BS	78.38	10.81	21.62	2.70
	TSA	78.38	-	21.62	-
IAMAX(27 stations)	MK	76.92	19.23	23.08	7.69
	MK BS	76.92	19.23	23.08	7.69
	TSA	76.92	-	23.08	-
IAMAX_JD (27 stations)	MK	44.44	0.00	55.56	0.00
	MK BS	44.44	0.00	55.56	0.00
	TSA	44.44	-	55.56	-
Max10(31 stations)	MK	74.19	19.35	25.81	0.00
	MK BS	74.19	19.35	25.81	0.00
	TSA	74.19	-	25.81	-
Max10_JD (31 stations)	MK	45.16	0.00	54.84	0.00
	MK BS	45.16	0.00	54.84	0.00
	TSA	45.16	-	54.84	-
Max30(37 stations)	MK	67.57	8.11	32.43	2.70
	MK BS	67.57	8.11	32.43	2.70
	TSA	67.57	-	32.43	-
Max30_JD (37 stations)	MK	16.22	0.00	83.78	2.70
	MK BS	16.22	0.00	83.78	2.70
	TSA	16.22	-	83.78	-
Min7(31 stations)	MK	90.32	16.13	9.68	3.23
	MK BS	90.32	16.13	9.68	3.23
	TSA	90.32	-	9.68	-
Min7_JD (31 stations)	MK	38.71	0.00	58.06	0.00
	MK BS	38.71	0.00	58.06	0.00
	TSA	38.71	-	58.06	-

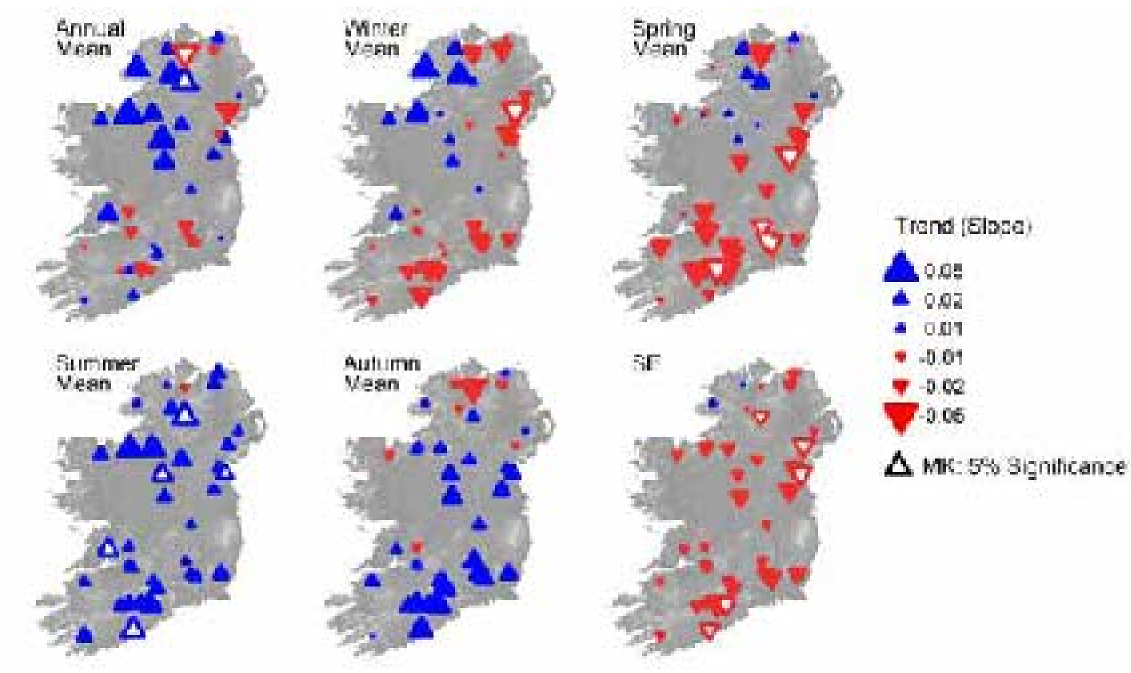

Figure 3.3. Trends in annual and seasonal mean flows and seasonality indicator (SE) for the fixed period 1976–2009. Increasing (decreasing) trends in blue (red), significance at 5 percent level is marked by a white infill. Magnitude of trend is plotted using the Theil-Sen Approach, while significance is tested using Mann-Kendall.

distribution towards increasing winter flows in the upper Shannon basin and the northwest and decreasing trends almost everywhere else. Spring mean flows are also dominated by decreasing trends across the country with increases, although weak and non-significant, found in the north of the island. Everywhere else, particularly to the south and east of the river Shannon large decreasing trends in spring mean flows are apparent, especially in the southeast where there is a cluster of significant trends.

In summer, mean flows show increasing trends across the country, with significant trends at the 5 percent level widely distributed. Large increasing trends are also found for autumn mean flows, especially in the south and southeast, although none of these are significant. There is a cluster of increasing trends in the north. Finally, the seasonality of flows, derived as a ratio of winter to summer mean flows shows decreasing trends throughout the island, with the exception of two weak increasing trends in the northwest. In the northeast and south there are clusters of significant trends.

3.5.2 Trends in High Flows 1976–2009

Indicators for both the magnitude and timing of high flows were analysed with results presented in Figure 3.4. IAMAX, the instantaneous 15-minute flow, shows significant increasing trends through much of the country, while in the northeast and northwest there are clusters of decreasing trends, two of which are significant. In terms of the timing of IAMAX no significant trends emerge for this time period, with weak increasing and decreasing trends dispersed throughout the island. MAX10 flow shows strong increasing trends throughout much of the island, particularly in the Shannon basin, west and southwest.

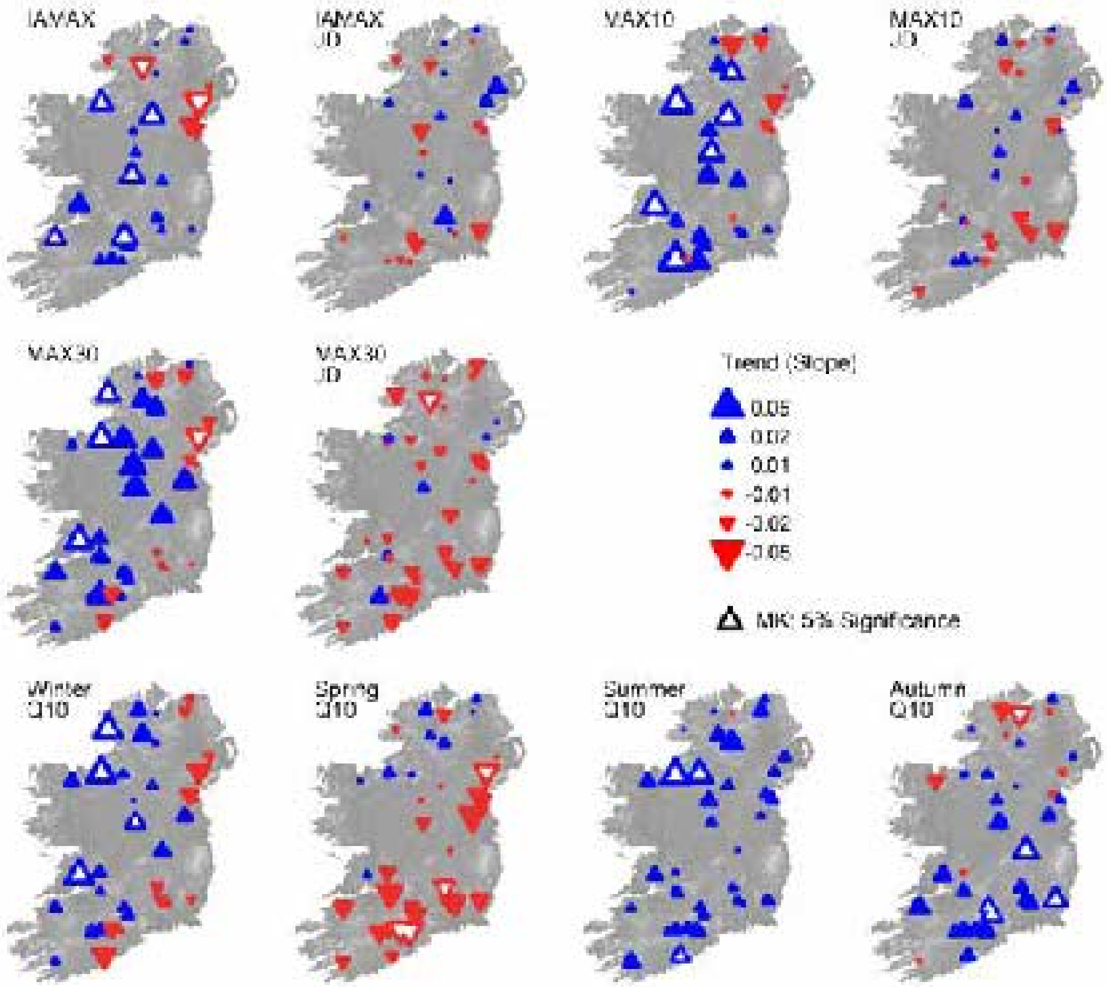

Figure 3.4. Trends in the magnitude and timing of high flows for the fixed period 1976–2009. Increasing (decreasing) trends in blue (red), significance at 5 percent level is marked by a white infill. Magnitude of trend is plotted using the TSA approach, while significance is tested using Mann-Kendall.

Small increasing trends are found in the southeast while decreasing trends are evident in the northeast. The timing of MAX10 shows no significant trends but large decreasing trends are apparent for the southeast in particular, indicating that this high-flow threshold is occurring earlier in the water year.

A similar spatial distribution is found for the magnitude of MAX30 day flows, with increasing trends throughout much of the island, with the exception of the northeastern, eastern and southern margins. While increasing trends are large, significant increasing trends are found only in the west of the country. In terms of the timing of MAX30 some large decreasing trends are evident in the south, southeast and northwest of the country, although non-significant, with the exception of one station in the northwest. Again, these indicate that the MAX30 flow is occurring earlier in the water year.

In addition to annual indicators, seasonal high-flow indicators were also analysed using seasonal Q10 values (flows equalled or exceeded 10 percent of the time). W_Q10 shows a strong spatial distribution with decreasing trends in eastern and southern areas, elsewhere increasing trends are apparent, particularly along Atlantic margins where a number of significant increasing trends are evident.

Trends in SP_Q10 are dominated by decreases, especially in the south of the island where a number of significant trends are derived. Weak increasing trends are found for the northwest, all non-significant. SU_Q10 shows increases for the entire island, but only three significant trends are apparent, two in the west/northwest and one in the south. In autumn decreases in Q10 are found in the extreme northwest, with increasing trends strongest in the south and southeast where a number of significant trends are found.

3.5.3 Trends in Low Flows 1976–2009

Trends in the magnitude and direction of low flows are presented in Fig. 3.5. The key low-flow variable used is MIN7 which represents the lowest 7-day consecutive daily mean flows in each calendar year and gives an indication of extreme low flows. Seasonal low flows were also analysed by employing seasonal Q90 flows, or flows that are equalled or exceeded 90 percent of the time. From the current research's entire analysis, the largest trends for the fixed period were found for the MIN7 flow (note the scale bar in Fig. 3.5). This indicator shows widespread increasing trends across the country, with a number of significant increases in the south, southwest and northwest. The timing of this extreme low-flow indicator has not shown any significant changes over the time period considered: however, there are some large decreasing trends in the south and east of the country, meaning that the MIN7 flow occurs earlier in the calendar year.

Surprisingly, W_Q90 is dominated by decreasing trends, particularly in the south, where there are a number of significant trends evident. Weak increasing trends are apparent for some stations in the northwest. SP_Q90 shows weak increases along coastal areas and weak decreases inland. Significant increasing trends are found in the upper Shannon and northwest. SU_Q90 is dominated by increases, with significant trends throughout the island. Again, these results are surprising given the expectation of lower flows in summer with anthropogenic climate change. However, the successive wet summers that have been experienced in recent years mean that the end of the record is dominated by extremes. A_Q90 is also dominated by increasing trends although there are fewer significant trends relative to summer, and trends in the west are weaker.

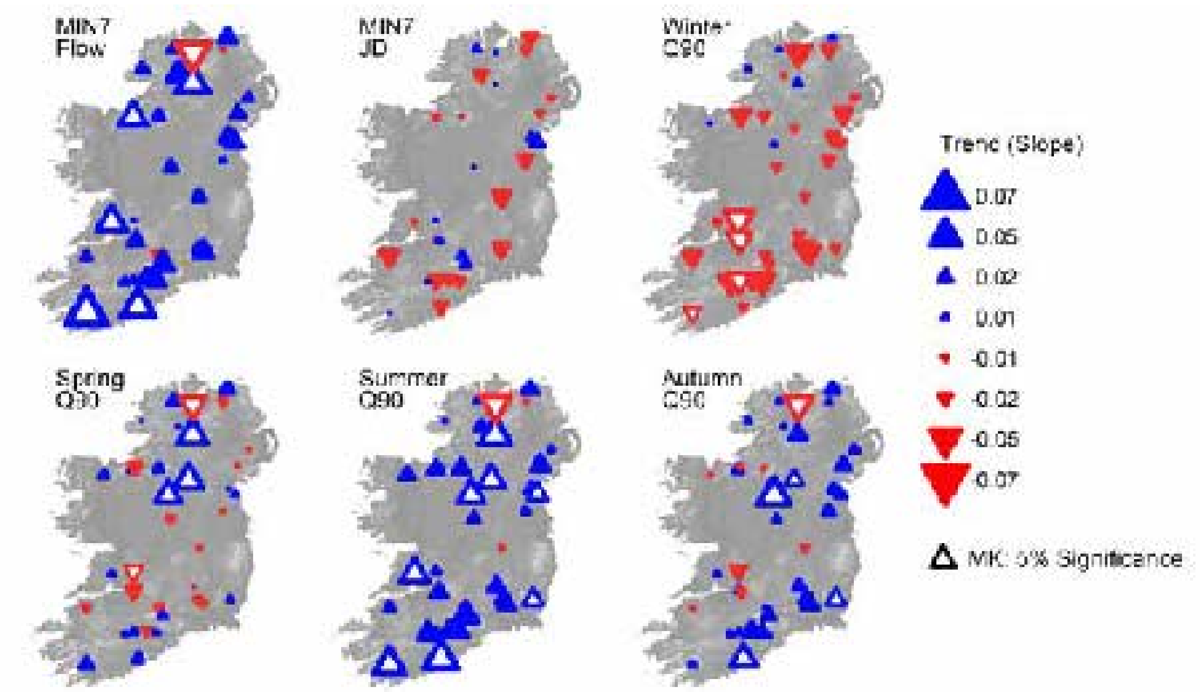

Figure 3.5. Trends in the magnitude and timing of low flows for the fixed period 1976–2009. Increasing (decreasing) trends in blue (red), significance at 5 percent level is marked by a white infill. Magnitude of trend is plotted using the TSA approach, while significance is tested using Mann-Kendall.

3.5.4 Variability of Trends and the Role of Extremes

This section explores how representative the fixed period is of variability in longer records and its sensitivity to extremes. In order to examine the role of variability in river flow records annual and seasonal mean flows from stations across the network were standardised and smoothed using Local Polynomial Regression Fitting (Loess). The seasonal mean flows are presented in Fig. 3.6: evident is the high degree of variability in the record.

Most stations in Ireland began monitoring in the mid-1970s for water-management purposes due to the drought conditions experienced at this time. As a result, for many stations there is a trend 'hard-wired' into results with the beginning of records commencing at one of the lowest points in the record and ending at the highest. This historical legacy makes the analysis of trends for fixed periods, where the emphasis is on optimising spatial coverage over record length, more difficult in the Irish context. These results highlight the importance of long records in the network, even if concessions need to be made on the criteria used to select stations. In spring, the change point identified by Kiely (1999) in precipitation and river flow records is evident for the late 1970s (Fig. 3.6). There is also a return to average conditions in spring mean flows around the mid-1990s. Summer and autumn are dominated by extremes at the end of the record.

Apparent from Fig. 3.6 is that quite different trend results can be derived depending on the period of record selected for analysis. For summer mean flows, as noted above, increasing trends are dominant throughout the island for the period 1976–2009. However, if small changes are made to the period of analysis, to exclude the extreme low flows at the start and extreme high flows at the end of the record, quite different results are derived (compare Fig. 3.7 with summer mean flows in Fig. 3.3). Therefore, the sensitivity of fixed periods is problematic for the analysis of trends unless their limitations are clearly communicated and results placed in the context of longer records.

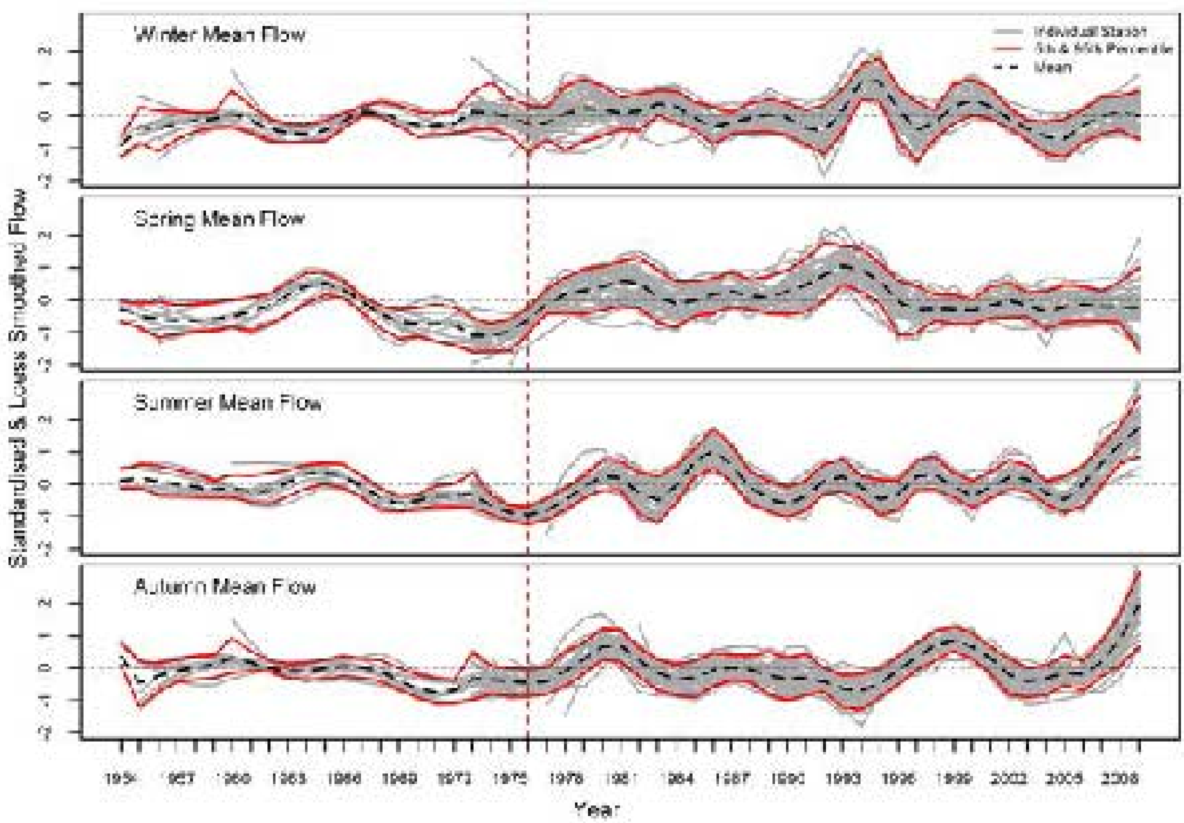

Figure 3.6. Standardised and Loess smoothed plots for seasonal mean flows for all stations in the Irish Reference Network (IRN). The vertical dashed line represents the start year (1976) for the fixed period of analysis.

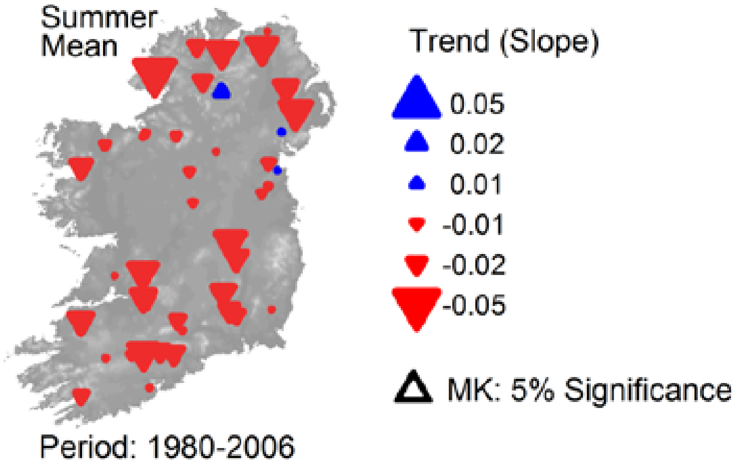

Figure 3.7. Trends in the magnitude and timing of summer mean flow for the period 1980–2006. Increasing (decreasing) trends in blue (red), significance at 5-percent level is marked by a white infill. Magnitude of trend is plotted using the TSA approach, while significance is tested using Mann-Kendall.

3.5.4.1 Correlation with the NAOI

Given the variability evident in flows the relationship of selected indicators to the North Atlantic Oscillation (NAO) was explored. The NAO is the dominant mode of climate variability in western Europe and influences storm tracks over the North Atlantic into Europe (Hurrell and Van Loon, 1997). The oscillation of the NAO between positive and negative modes is described by the North Atlantic Oscillation Index (NAOI). The winter NAOI is most discernible and exhibits significant inter-annual and decadal variability (Hurrell, 1995). Since 1864 the NAOI is known to have changed sign over time. During the last half century the index was largely negative until the late 1960s after which a strong positive trend persisted until the mid-1990s (Wilby *et al*., 1997). Since then, the NAOI has exhibited a negative trend culminating in 2009/2010 with one of the most negative NAOIs on record (Pinto and Raible, 2012).

To investigate the relationship (linear association) between the NAOI and selected indicators for the fixed period 1976–2009, Spearman's rank correlation was employed. Compared to the widely used Pearson correlation, Spearman's rank correlation test is less sensitive to outliers, and, because it ranks the data, it does not have the assumption of normality. Significance testing was conducted at the 5 percent significance level with a null hypothesis of no linear association and alternative hypothesis of negative or positive linear association. For the analysis, seasonal NAOI series were obtained from the National Center for Atmospheric Research (NCAR) where, in line with the seasonal categorisation for flow indicators, the winter NAOI was defined as DJF. Attention was given to assessing correlations of flow indicators with winter and spring NAOI. Lagged correlations were also derived with summer mean flows to test if they were correlated with the previous winters' NAOI. Correlation results are presented in Fig. 3.8. Winter mean flows show widespread positive correlation with the winter NAOI, particularly for stations in the southwest and northwest where significant positive correlations are evident. Stations along eastern and southern coastal areas show non-significant negative correlations. Summer mean 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. While surprising, this relationship has also been identified for stations in the east and southeast of the UK by Wedgbrow *et al.* (2002) who hypothesised that this relationship was caused by storage effects in catchments. Understanding these relationships further and the potential offered for seasonal forecasting of summer water resources should be explored in greater detail. For MAX10 flows, which are predominantly found in winter months, statistically significant positive correlations with winter NAOI are evident along Atlantic margins. Further east, correlations become non-significant and non-significant negative correlations are found along the eastern seaboard. Spring NAOI

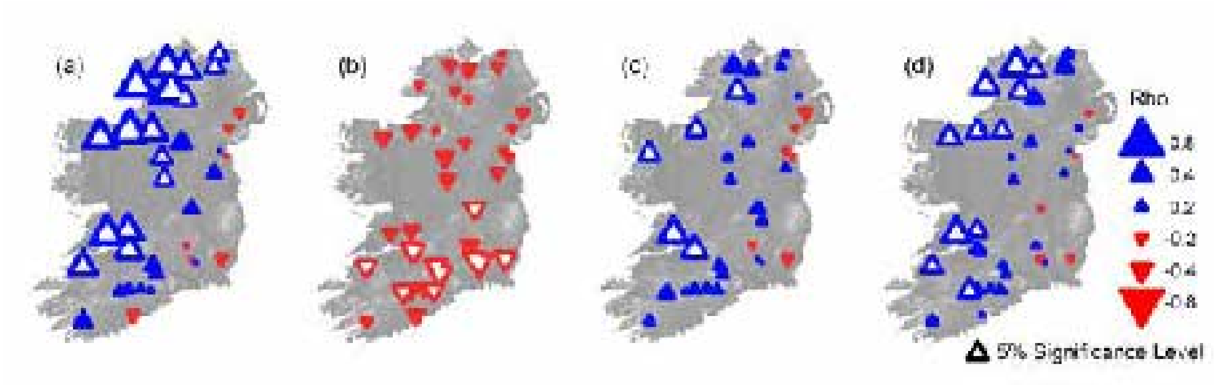

Figure 3.8. Spearman's rank correlation between North Atlantic Oscillation Index (NAOI) and selected indicators. (a). Winter mean flow and winter NAOI, (b). Summer mean flow and previous winter NAOI, (c). MAX10 and winter NAOI and (d). Spring mean flow and spring NAOI. Positive correlation are blue, significant correlations are infilled in white.

correlation with spring mean flows shows significant relationships in the western half of the country, becoming weaker and negative further east.

3.6 Persistence of Trends

Given the sensitivity of the fixed period to chosen dates, the persistence of trends was examined by systematically reducing the start year of analysis from the full record at individual stations to a minimum of 30 years following the approach of Wilby (2006) and Hannaford and Buys (2012). For each indicator, the MK Z statistic (Zs) 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, for example, 56 and 30 years. Plotting Zs values for each iteration allowed a fuller appreciation of the evolution of trend and also an indication of the persistence of any significant trends throughout the period of record. The presentation of results is again organised into mean, high and low flows.

3.6.1 Persistence of Trends – Mean Flows

In Fig. 3.9 most annual mean flow records show increasing trends across Ireland that are statistically significant for longer records. However, there is evidence of a major change in the strength and direction of trends across the network for tests beginning after the mid-1970s where significance of trends in longer records is lost. Even stations with significant increasing trends throughout the record show a shift to decreasing trends for tests beginning in the late 1970s.

There are few significant trends in winter mean flows (Fig. 3.9) throughout the record; however, there is a tendency for increasing trends for longer records, though non-significant, with the exception of one station in the west. For winter there is a likelihood of weaker trends for all records (both positive and negative) for shorter records. For stations in the south and northeast in particular there is a tendency for strong and significant negative trends in winter for series 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 for series commencing after the mid-1970s.

Spring mean flows (Fig. 3.9) display very similar, but more pronounced, results relative to the annual mean and point to the influential role that changes in spring have at the annual level. There are large changes in the direction and significance of trends for spring means, with earlier start dates showing a tendency for strongly positive trends. However, trend tests commencing in the early 1960s and later show tendencies for weak positive or negative trends. For series commencing in the mid-1970s there is a considerable change in direction of trends with spring trends becoming significantly negative for many stations.

By varying start years summer mean flows show persistent positive trends, with particularly significant increases for earlier start dates for long records in the southeast. Extended drought conditions in the early 1970s weaken the strength and significance of trends from this period onwards. In autumn (Fig. 3.9), trends are

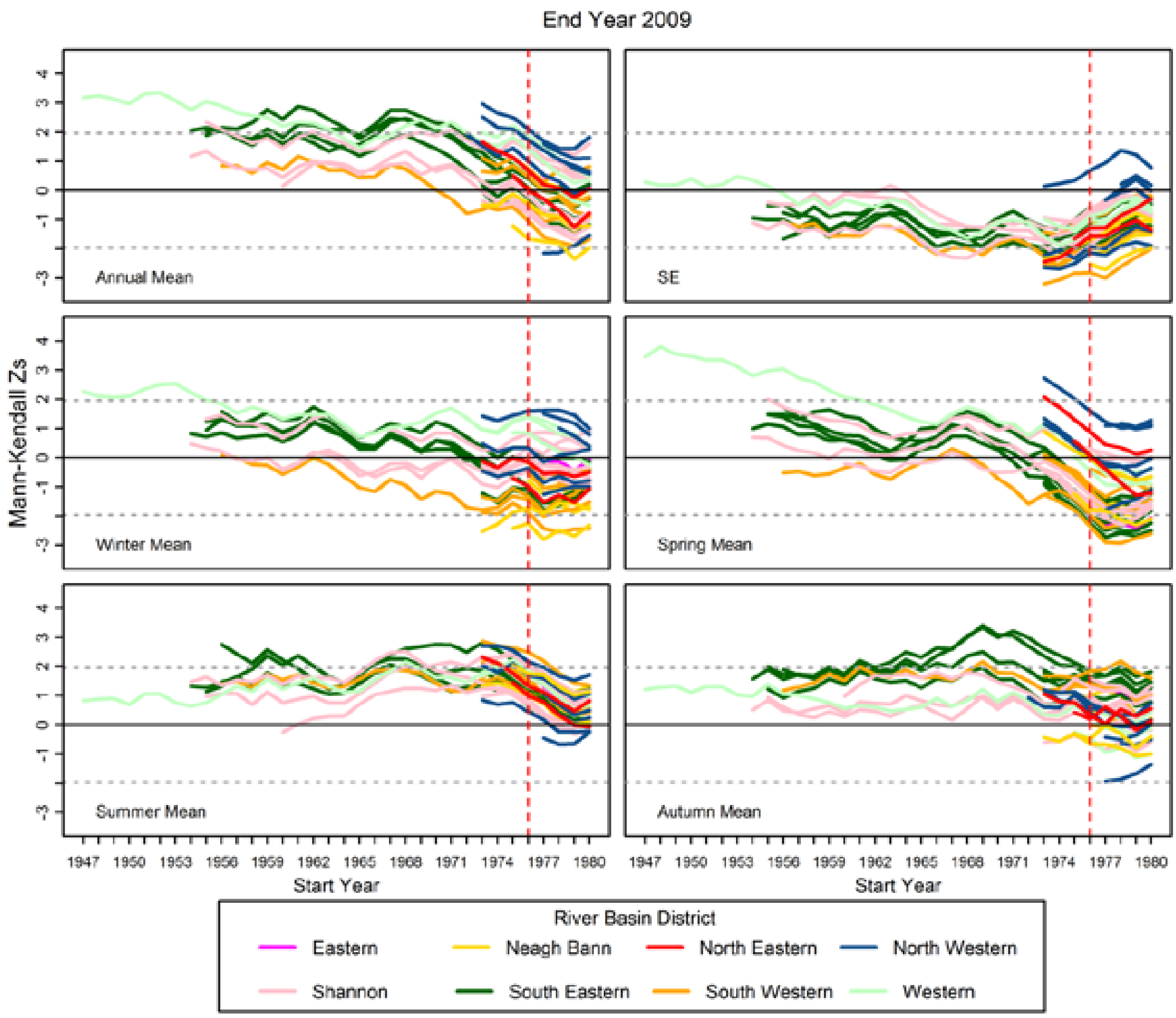

Figure 3.9. Persistence of trends in annual and seasonal mean flows and seasonality for the full period of record for each station in the Irish Reference Network (IRN). Results are presented using MK Zs statistic with the dashed horizontal lines defining significant increasing/decreasing trends at the 5 percent level. Dashed red line represents the start of the fixed period of analysis 1976–2009.

less subject to variability, but the impact of the mid-1970s low flows is also visible, most notably in the southeast and resulting in significant increasing trends for these start years. In line with trends in summer and winter mean flows, the seasonality indicator (ratio of winter to summer flows) shows negative trends throughout most of the record, with the exception of stations in the west and northwest. Many of the decreasing trends in seasonality are strong and at times significant, particularly for trends beginning in more recent decades.

In Fig. 3.10 trend analysis ends in 2006 to show the impact of end-of-record extremes on the strength and significance of trends in mean flows, which can be seen to affect even the longest records. When extremes at the end of the record are removed, there is a general reduction in the MK Z statistic (represented as a downward shift in the position of the plotted lines), resulting in a large reduction in the number of significant positive trends in summer means, and a greater proportion of negative trends, particularly since the mid-1970s. However, longer records remain dominated by increasing trends in summer mean flows. Winter flows also show a higher proportion of negative trends when extremes at the end of the record are removed. Therefore, in both winter and summer mean flows there is a notable lack of significant trends throughout the network with the direction of trends highly dependent on the start and end year of analysis.

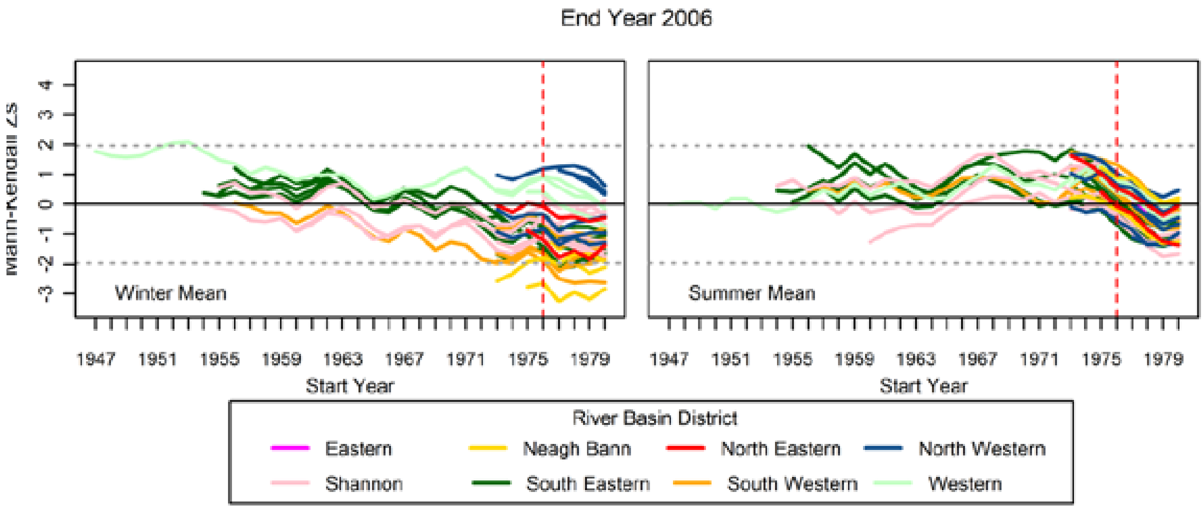

Figure 3.10. Persistence of trends in winter and summer seasonal mean flows for year ending 2006. Results are presented using MK Zs statistic with the dashed horizontal lines defining significant increasing/decreasing trends at the 5 percent level. Dashed red line represents the start of the fixed period of analysis 1976–2009.

3.6.2 Persistence of Trends – High Flows

Figure 3.11 shows the persistence of trends in high flows. Strong increasing trends are apparent in IAMAX for most stations throughout the record. Although some decreasing trends are found, longer records tend to show stronger and more significant trends. In terms of timing of flows, persistent non-significant trends are evident throughout.

MAX10 also shows persistent positive trends for the majority of stations. Strong positive trends are apparent for series beginning in the mid-1950s and early 1970s. Similar results are evident for MAX30 day flows. Strong positive trends are associated with earlier start years, again emphasising the importance of longer records for contextualising results based on shorter series. Records beginning in more recent decades show a decrease in the strength and significance of trends for both IAMAX and MAX30. By altering the end year of analysis to 2006 (not shown, but similar to Fig. 3.10) it was found that trends in IAMAX were also influenced by extremes at the end of the record. While trends remained strongly positive for many stations there were fewer stations with significant trends for short records when the effect of end-of-record was removed. Both of the longer duration high-flow indicators (MAX10 and MAX30) are less sensitive to outliers at the end of record, suggesting a greater robustness of trends in these variables.

From Fig. 3.11, seasonal high flows (Q10) show a very similar pattern in the persistence of trends to the seasonal mean flows, indicating the influencing role of high flows on mean conditions. Longer records for W_Q10 show a tendency for both increasing and decreasing trends. Earlier start dates in the longer records show a tendency for increasing trends; however, it cannot be stated with confidence that all stations would show this tendency. In spring a similar transition from positive to negative trends that was found in spring mean flows is also apparent for SP_Q10 flows. Summer high flows are dominated by increasing trends throughout the record. However, with summer, as noted above, care needs to be exercised due to extremes (high Q10 flows) at the end of the record. Autumn high flows are also dominated by increasing trends for longer records, particularly in the southeast where significant increasing trends are found for analysis beginning in the years 1959 through to the late 1970s.

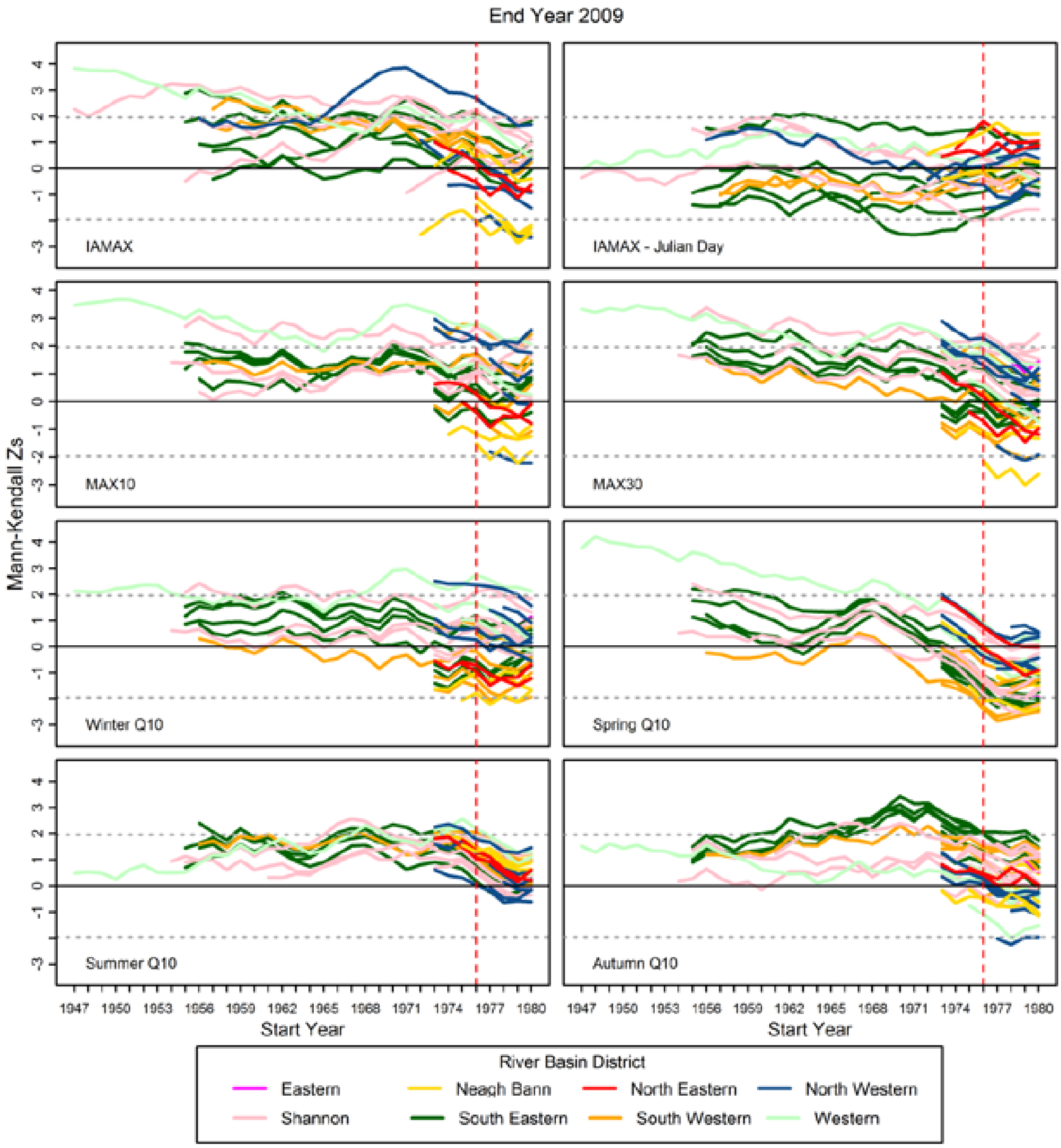

Figure 3.11. Persistence of trends in high-flow indicators for the full period of record for each station in the IRN. Results are presented using MK Zs statistic with the dashed horizontal lines defining significant increasing/decreasing trends at the 5 percent level. Dashed red line represents the start of the fixed period of analysis 1976–2009.

3.6.3 Persistence of Trends – Low Flows

Figure 3.12 shows the persistence of low-flow trends. Fewer long records are employed for the analysis of MIN7 due to the lower quality rating for some stations for low flows. The majority of stations show increasing trends for all start dates. Significant increasing trends at the 5 percent level are apparent for a number of stations beginning in the period from the mid-1960s, reflecting the influence of the mid-1970s' drought conditions. Very large increasing trends are evident for shorter records and begin at the driest period in the observational record. Only one station in the southeast shows a persistent decreasing trend, although this is non-significant throughout. The timing of MIN7 flows

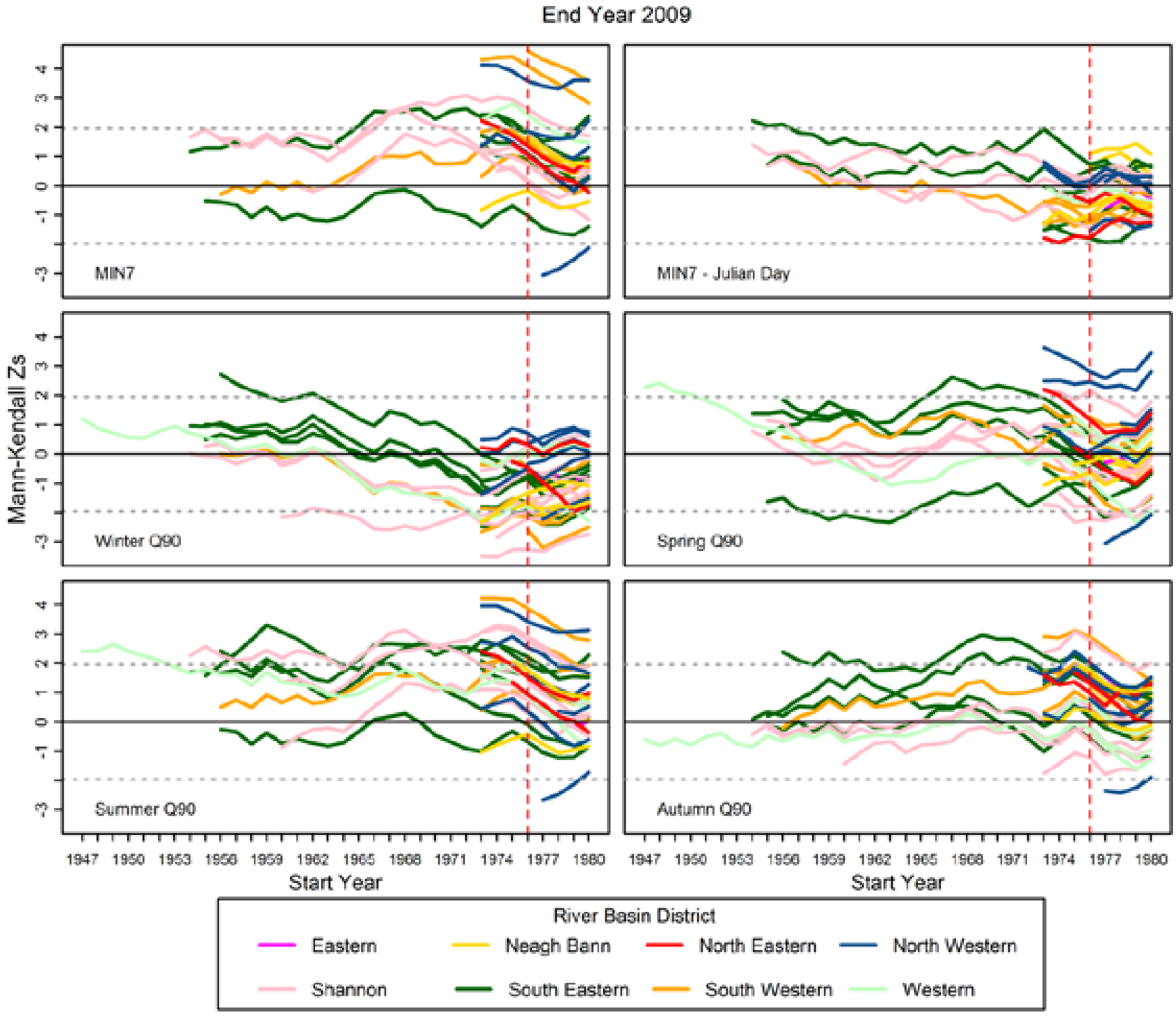

Figure 3.12. Persistence of trends in low-flow indicators for the full period of record for each station in the Irish Reference Network (IRN). Results are presented using MK Zs statistic with the dashed horizontal lines defining significant increasing/decreasing trends at the 5 percent level. Dashed red line represents the start of the fixed period of analysis 1976–2009.

(JDs) shows one station with a significant trend for three individual start years, while generally there is a mix of both positive and negative trends with a slight shift to a negative trend (earlier occurrence of the 7-day low-flow period) over time. Seasonally, Q90 flows in winter show increasing trends for long records, but there is a transition towards decreasing trends for records beginning in the early 1960s. Trend tests beginning in more recent decades are largely negative with the exception of individual stations in the northwest and northeast which reveal only weak increasing trends. While the direction of trends in SP_Q90 is quite mixed, there is evidence of a shift towards more negative trends for tests beginning in the mid-1970s. Summer low flows show persistent increasing trends throughout the record for the majority of stations. Only one station in the northwest shows a significant decreasing trend. In A_Q90 flows there are few significant trends with longer records showing a mixed picture. There is however some spatial pattern evident with positive trends in the southeast and southwest compared to negative or no trends in the Shannon and west.

3.7 Moving Windows Analysis

In the previous section the influence of the start year of analysis on the trends derived was shown. This section explores the influence of both varying start and end years by analysing trends for all possible combinations of start and end years (‘moving windows’) for the long records in the reference network. For comparison across stations, the longest possible period 1956–2009 was selected for analysis. The long record lengths used mean that the spatial distribution of stations included was limited. The emphasis of this analysis was on understanding in more detail the variability of trends, identifying any changes in direction of trends, the influence of start and end dates on trends and identifying when significant trends emerge from the data. Appendix 2 provides further guidance for interpreting the moving windows plots. For ease of presentation results are presented only for selected indicators. Appendix 3 provides the output for all other indicators. In keeping with the above analysis, results are presented separately for each part of the flow regime. Depending on the indicator analysed the number of stations included varies.

3.7.1 *Moving Windows – Mean Flows*

From Fig. 3.13 trends for annual mean flows show a change in direction around 1980. For longer record series there is a shift towards increasing trends for time series ending after 1980. However, for shorter records (beginning around the mid-1970s) decreasing trends are found. In terms of significance, tests beginning before 1970 show significant increases emerging for records ending after the 1980s.

Figure 3.14 shows seasonal mean flows. For winter the lack of significant trends is apparent. Earlier start dates representing longer records show increasing trends, while trend tests beginning from the mid-1970s onwards show decreases. For all stations spring mean flows are marked by a change in trend direction (from decreasing to increasing) for time series ending around 1980. The largest number of significant trends are found for analyses beginning around 1970: however, these do not persist after the mid-1990s. Shorter series, beginning around the 1980s, show decreasing tends for all stations. For trend tests ending after 2000 there are few significant trends across all long record stations.

Summer mean flows (Fig. 3.14) show increasing trends for long records/early start years. A strong end of record effect is apparent where the last two years of record show increasing trends, which are significant at the 5 percent level. Following the dry mid-1970s some stations show significant increasing trends from short records ending in the 1980s, but these do not persist. While results for autumn mean flows are mixed, there is some evidence for a change in direction of trends from decreasing to increasing, again for records ending around 1980. Time series beginning around the 1970s show the highest number of significant trends, particularly for trend tests ending after 2000.

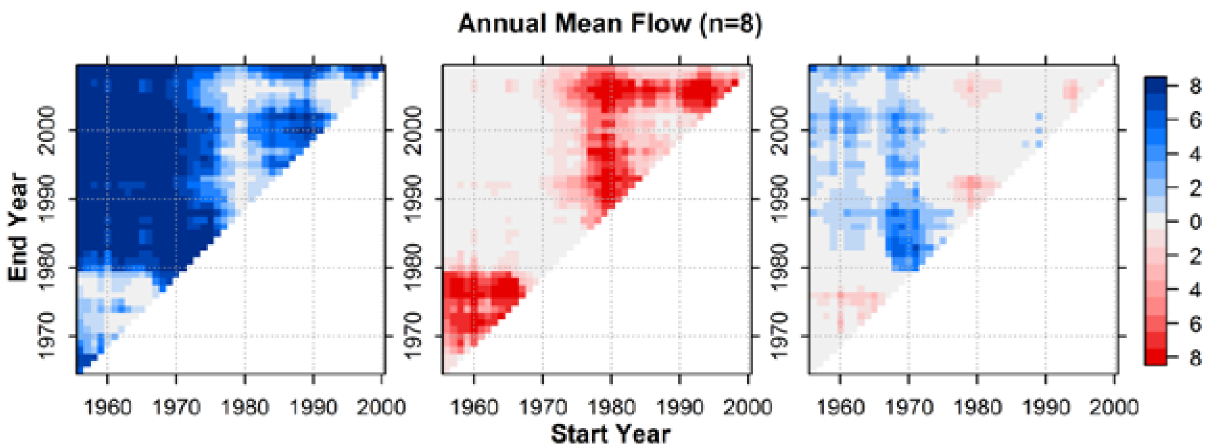

Figure 3.13. Moving windows analysis of all possible start and end dates in annual mean flows for 8 long record stations. Left panel shows the number of stations showing increasing trends, the centre panel shows the number of stations showing decreasing trends, while the right panel shows the number of significant trends derived using the Mann-Kendall test. Significance is tested at the 5 percent level. n indicates the total number of stations analysed (n varies with indicator).

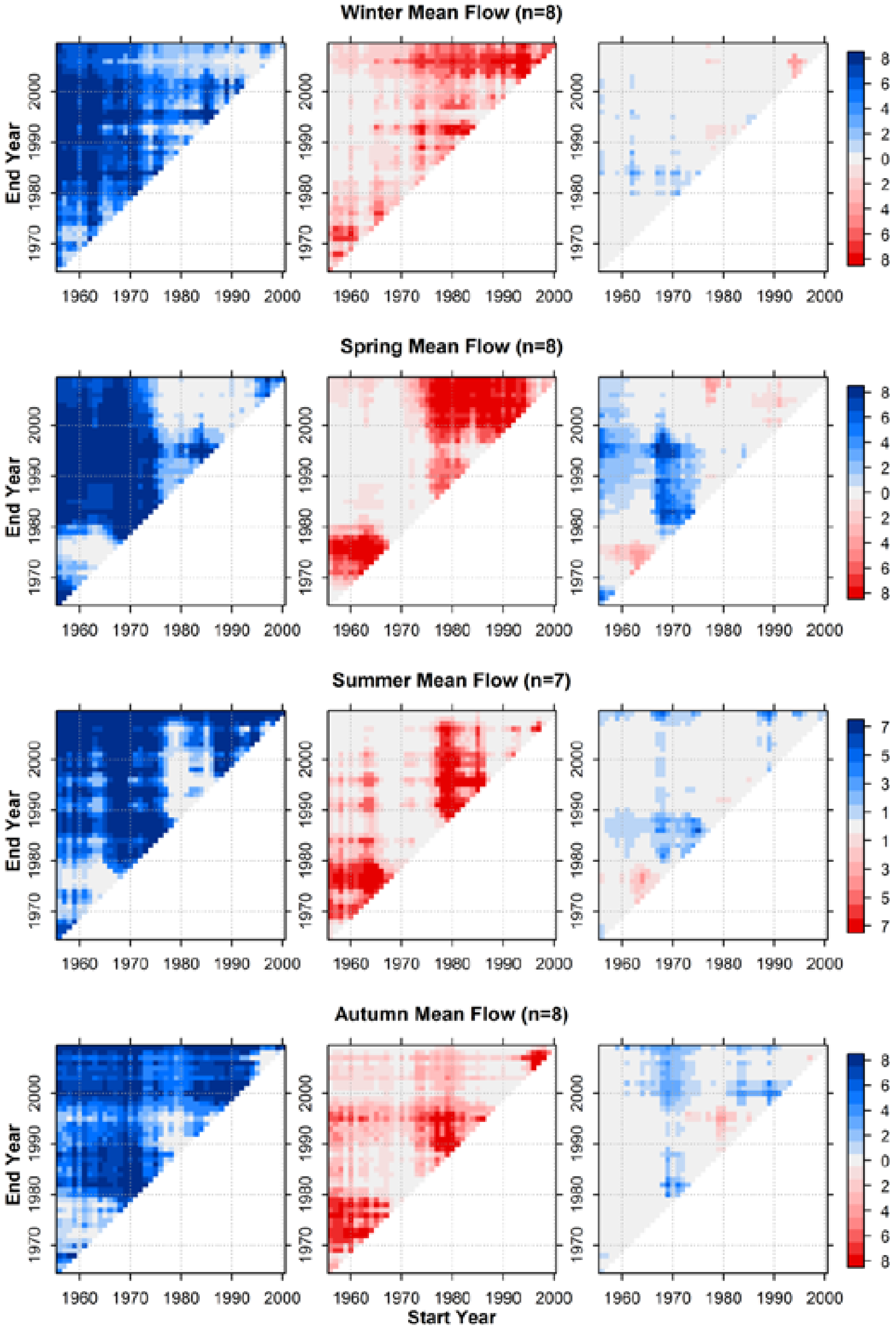

Figure 3.14. Moving windows analysis of all possible start and end dates in seasonal mean flows for long record stations. Left panel shows the number of stations showing increasing trends, the centre panel shows the number of stations showing decreasing trends, while the right panel shows the number of significant trends derived using the Mann-Kendall test. Significance is tested at 5 percent level (n indicates the total number of stations analysed).

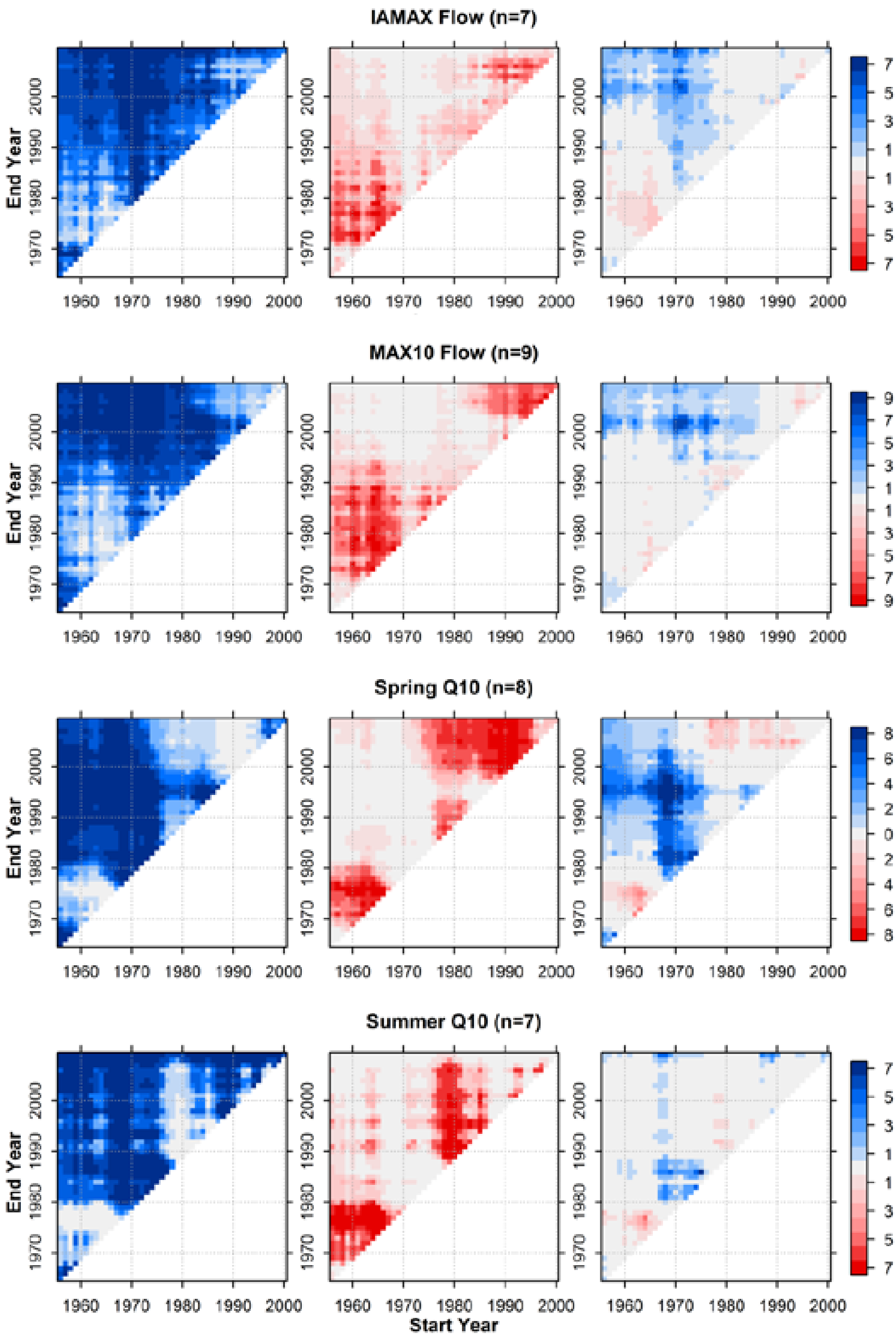

Figure 3.15. Moving windows analysis of all possible start and end dates in high-flow indicators for long record stations. Left panel shows the number of stations showing increasing trends, the centre panel shows the number of stations showing decreasing trends, while the right panel shows the number of significant trends derived using the Mann-Kendall test. Significance is tested at 5 percent level (n indicates the total number of stations analysed).

3.7.2 Moving Windows – High Flows

From Fig. 3.15 early start years/long records show increasing trends in IAMAX. Interestingly, high numbers of significant (5 percent level) increasing trends only emerge from 2000 onwards, and only for records that begin before the late 1970s. In long records there is also a change in direction for trends in IAMAX around 1990 when trend tests ending before 1990 are negative. Shorter records show no significant increases in IAMAX. Similarly, for MAX10 day flows increasing trends in longer records have emerged as significant from 2000 onwards. There is some evidence of a change in direction of trends for MAX10, from decreasing to increasing trends around 1990, although these trends are not significant.

For seasonal high flows (Fig. 3.15), results are presented only for spring and summer_Q10. The results for both Q10 indicators are very similar to seasonal mean flows. For long records a large change in direction in SP_Q10 is evident for records ending after 1980. Trend tests beginning in the late-1960s and early-1970s show a high number of significant trends for time series ending from 1980s onwards and that persist through the 1990s, but become non-significant for records ending after 2005. Time series beginning in the late 1970s onwards show decreasing trends in SP_Q10. SU_Q10 also shows a change in direction for tests ending after 1980. Decreasing trends are evident for start years from the mid-1970s until recently. There is a return to significant increasing trends in 2008–2009, indicating the influential role of recent wet summers. However, overall there is a lack of significant trends for SU_Q10, with any significant trends being highly dependent on start and end years.

3.7.3 Moving Windows – Low Flows

The analysis of MIN7 flows (Fig. 3.16) shows that records beginning before 1965 show mixed results for the long record stations, where both increasing and decreasing trends are apparent with a low number of significant trends. For trend tests beginning around 1970 significant increasing trends emerge – indicating the sensitivity of trends in MIN7 flow to the low-flow conditions of the early 1970s. Trends are also heavily influenced by the wet end of record.

W_Q90 shows increasing trends for longer records/earlier start years. While many of the long record stations show significant increasing trends for analyses that end in the mid-1980s, only a few significant trends remain from the 1990s onwards for the earliest start dates. For records beginning in later decades, there is a shift towards decreasing trends, particularly for those starting in the 1970s, for which some stations show significant decreases. For SU_Q90 the majority of long record stations show increasing trends, particularly for analyses ending after 2000, again indicating the importance of extremes at the end of the record. Persistent significant increasing trends are evident for series beginning around the late 1960s. For long record trends ending before 2000 there are mixed results with some stations showing decreasing trends; however, the number of significant positive trends far outweighs the number of significant decreasing trends.

3.8 Conclusions

This work provided an in-depth analysis of trends in the IRN. Trends were analysed using three approaches to examine the spatial distribution of trend for a common, fixed period, to assess the persistence of trend for varying start years and to examine the variability of trends for all possible combinations of start and end years. In concluding the analysis a summary of key trends are presented and a discussion on possible drivers of change within the network provided. In terms of attribution, this does not go beyond the ‘soft’ attribution discussed by Merz *et al.* (2012). Summaries of results are given separately for mean, high and low flow indicators.

3.8.1 Summary of Trends

3.8.1.1 Mean-flow results summary

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:

Annual mean flows – Longer records tended towards statistically significant (5 percent level) increasing trends. Shorter records showed non-significant decreases. No clear spatial distribution emerged from the analysis. Understanding the seasonal contributions of changes in annual means is highly complex, with

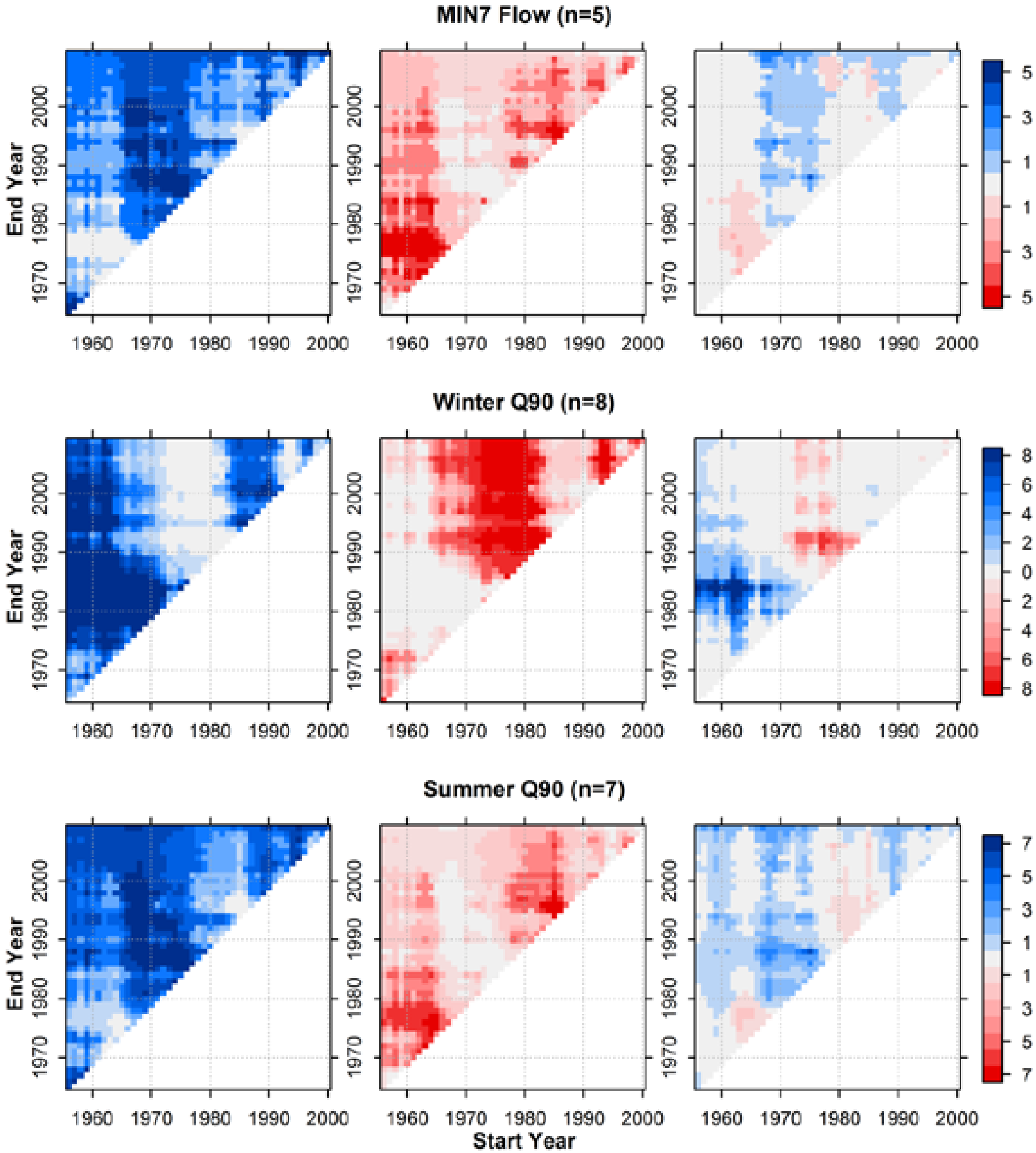

Figure 3.16. Moving windows analysis of all possible start and end dates in low-flow indicators for long-record stations. Left panel shows the number of stations showing increasing trends, the centre panel shows the number of stations showing decreasing trends, while the right panel shows the number of significant trends derived using the Mann-Kendall test. Significance is tested at 5 percent level (n indicates the total number of stations analysed.

evidence of different seasons having influences for different parts of the record.

Winter mean flows – From the fixed period, increases were found only for stations in the west and northwest with decreasing trends in the east and south and particularly strong in the northeast. For longer records there was a tendency towards non-significant increasing trends, which were 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 showed a tendency for increasing trends.

Spring mean flows – 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 showed a tendency for strong and significant increasing trends. In recent decades a strong transition to decreasing trends was found, especially in the south and southeast.

Summer mean flows – From the fixed period, summer means were dominated by increasing trends, some of which were 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 remained 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 persisted. Summer mean flows showed the largest disagreement with projected future climate scenarios of substantial reductions in summer flows.

Autumn mean flows – Autumn mean flows were also dominated by increasing trends throughout the record, with the largest trends in eastern and southern regions. Persistent significant and near significant increasing trends were evident for long records in the southeast. The 1970s' drought has also had a bearing on trends for autumn mean flows.

Seasonality – The ratio of winter to summer mean flows showed decreasing trends throughout the record, indicating a reduction in seasonal differences. This is in line with decreasing trends in winter and increasing trends in summer in recent decades and is contrary to the increased seasonality expected from projected climate change scenarios. With longer records there was a tendency for increasing seasonality.

3.8.1.2 High-flow results summary

Overall, the majority of high-flow indicators were dominated by increasing trends, a high number of which were significant. For annual (IAMAX, MAX10 and MAX30) and winter high flows (Q10), statistically significant trends have emerged only for records ending after *c.*2000, even for the longest records. For these indicators, trend tests ending before the 1990s showed decreases in extremes. The relative magnitude in the spatial distribution of trends from the fixed period was generally coherent for longer records.

IAMAX **–** Instantaneous 15-minute flows showed persistent increasing trends. Larger trends were evident for longer records. For longer records the significance of trends has largely emerged for records ending after 2000. Short records revealed no significant trends for IAMAX.

MAX10 **–** Maximum consecutive 10-day flows showed persistent increasing trends in the western half of the country and also in the southeast. Longer records showed stronger trends. Long record trends in MAX10 have also become significant since *c.*2000. Short records showed fewer significant trends.

MAX30 **–** Showed a tendency for significant increasing trends in long records. Shorter records showed fewer significant trends with stations in the northeast and southeast showing decreases.

Seasonal high flows (Q10) **–**The spatial and temporal evolution of trends in spring and summer Q10 flows were remarkably similar to trends in mean flows for corresponding seasons. SP_Q10 showed the same loss of significance in long records for trends ending after the early 2000s. This indicates the important contribution that seasonal high-flow changes have in driving trends in seasonal mean flows.

3.8.1.3 Low-flow results summary

Low flows were found to be heavily influenced by the drought in the 1970s, the historical legacy of network expansion and wet years at the end of records, making it extremely difficult to extract robust trends. The timing of low flows showed little evidence of significant trends. Low flows also showed the greatest range in the strength and direction of trends.

MIN7– No significant decreasing trends throughout the record were evident (apart from one station in Northern Ireland). Increasing trends were dominant for records starting in the 1970s. Longer records showed no clear direction or patterns of trend.

Seasonal low flows (Q90) – For W_Q90 long records showed a tendency for increasing trends. However, records beginning in the mid-1960s onwards showed decreases, some of which were significant. No long-term persistent trends were found. SP_Q90 showed a lack of long-term significant trends, with large variability throughout the record. SU_Q90 was dominated by increasing trends for the majority of stations. Significant trends were widespread throughout the record. A_Q90 was also dominated by increasing trends, although fewer statistically significant trends than SU_Q90 were apparent. Longer records showed mixed weak trend.

3.8.2 *Attributing Drivers of Change*

Particularly evident from the plots showing the persistence of trends is the coherence of results for each indicator across the entire network. This consistency gives confidence that the network is fit for purpose and that trends are driven by forces external to the catchment. Trends in seasonal mean flows were also compared with those derived from seasonal precipitation totals from eight rain gauges across the country. The persistence of trends in seasonal precipitation totals is shown in Fig. 3.17. The results show a close correspondence with those found for river flows. Evident for winter precipitation is a lack of long-term statistically significant positive trends. Long records for spring precipitation show a tendency for positive trends, with the same transition as in spring mean flows to negative trends evident in recent decades. The longest-term series for summer precipitation totals show strong positive and weak negative trends.

The agreement between trends in seasonal precipitation and river flows adds confidence to the results given that trends are derived from different data sources. Seasonal mean trend results from the IRN are also remarkably similar to results from the UK Benchmark Network (Hannaford and Harvey, 2010; Hannaford and Buys, 2012) and other UK studies (Dixon *et al*., 2006). Regional similarities with the UK and the coherence of results with precipitation records in Ireland support the view that the hydrometric stations selected for the IRN are fit for purpose. The results also suggest that the trends in both regions are being forced by a common, external climate driver.

The transition from increasing trends in longer records towards decreasing trends in both spring flow and precipitation is also evident from the analysis of trends in the UK and parts of Europe (Hannaford and Buys, 2012) and indicates a regional-scale driver of change. Loss of significant increasing trends in spring

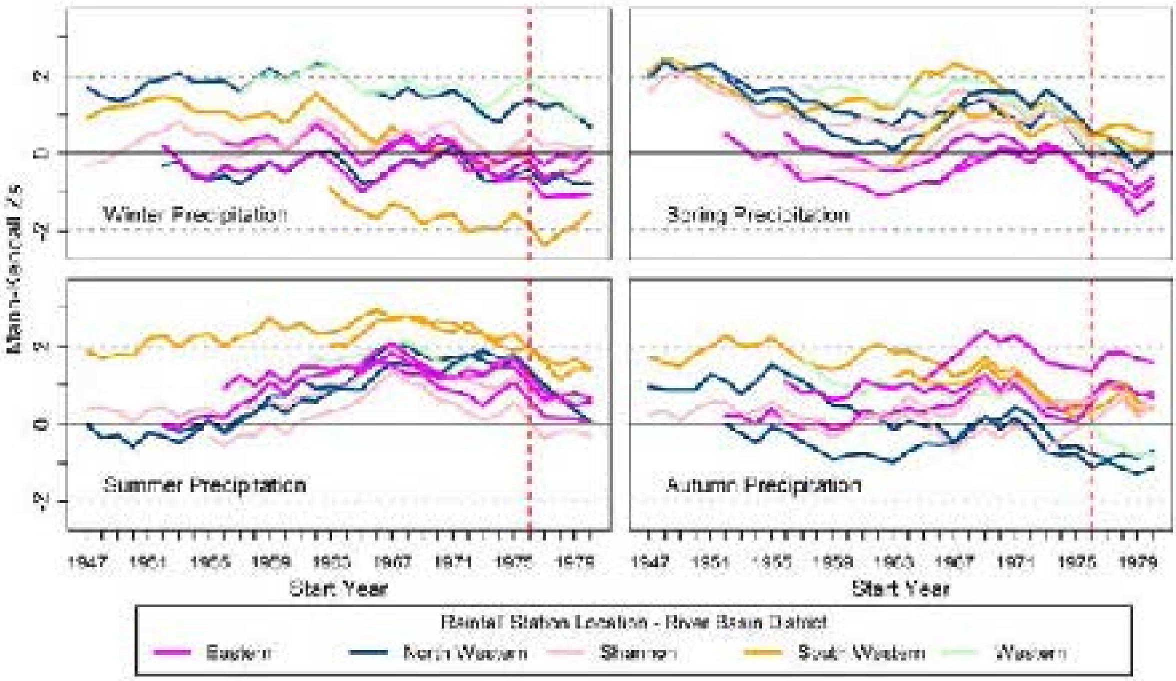

Figure 3.17. Trends in seasonal precipitation totals for eight stations across the country. Results are presented using MK Zs statistic with the dashed horizontal lines defining significant increasing/decreasing trends at the 5 percent level. The dashed vertical line represents the start of the fixed period used for the analysis of trends in river flows (1976–2009).

mean flows for longer records, some of the largest trends identified in the analysis, and the shift towards decreasing trends in recent decades is surprising given the findings of Kiely (1999) and Leahy and Kiely (2011) for March flows and precipitation. Differences in methodological approaches offer some insights where previous work has examined changes pre- and post-the NAOI change point; whereas here we analysed the evolution of trends over time. The Loess plots in Fig. 3.6 also show that while a change point in spring mean flows is evident in the mid-1970s and persists until the mid-1990s it is apparent that SP_Mean flows have returned to a lower state since then. This shift is likely responsible for the transition from increasing to decreasing trends experienced in spring and is consistent with more negative NAOI anomalies.

High flows showed the greatest number of significant and persistent trends and were strongly correlated with the NAOI in western areas. Strong relationships between high flows and the NAOI have also been found in other studies internationally (Villarini *et al*., 2012; Hannaford and Marsh, 2008). Mean and high flows did not always show the same direction of change, the most striking being winter mean flows and IAMAX for the fixed period of record, although longer records for both showed increasing trends. Even so, trends in winter high flows were stronger than for winter means. Similar characteristics of change were also found for precipitation by Leahy and Kiely (2011). Minimisation of confounding factors in the reference network increases confidence that derived trends are not predominantly driven by internal catchment change.

While there is considerable evidence of variability and change in the hydrological indicators derived from the flow records in the IRN, it is difficult at this time to attribute changes to greenhouse gas induced climate change. In fact, some of the trends that were found in flow indicators are not consistent with those expected from future climate change scenarios as simulated by Global Climate Models. Such disparities have also been found and commented on by others (e.g. Svensson *et al*., 2005; Wilby, 2006; Wilby *et al*., 2008; Hannaford and Marsh, 2008; Fowler and Wilby, 2010) and are likely due to the low signal-to-noise ratio of the climate change signal compared to natural climate variability. Of particular note were the observed trends in winter and summer mean flows which reveal apparent contradictions with projections of wetter winters and drier summers with anthropogenic climate change. While longer records showed increases in winter flows these trends were lost, and even showed decreases for series beginning in recent decades. It should also be borne in mind that uncertainties associated with predicted climate change impacts can be large and even span sign changes which makes confident attribution of observed trends more difficult.

While trends in specific indicators showed a significant correlation with the NAOI, how the NAO itself will respond to anthropogenic climate change remains an open question. Indeed, debate is ongoing as to whether greenhouse gas emissions have had a significant influence on the recently persistent positive phase of the NAOI (Osborn, 2004; Dong *et al*., 2011). Using the CMIP2 ensemble of Global Climate Models, Stephenson *et al*. (2006) show that future NAO response to heightened greenhouse gas concentrations is small and highly model dependent, with the NAO unlikely to be a key contributor to predicted increases in winter precipitation in Europe. They also highlight the inability of Global Climate Models to capture the observed decadal variability in the NAO.

Finally, it should be noted that the NAOI provides limited information for attributing change and recent studies have pointed to the potential of variables more suited to attribution, such as sea surface temperatures (SSTs) (Lavers *et al*., 2010). Research points to solar variations in causing the negative NAO-like conditions associated with dry winters (Ineson *et al.*, 2011) whilst sea ice is also thought to be influential in causing jet stream changes (Francis *et al.*, 2009), which have been so influential in recent years. Of particular interest are the recent findings of Sutton and Dong (2012), which show that the warming of North Atlantic SSTs 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.

4 Detectability of Climate Change Signals

4.1 Introduction

Results from Section 3 suggest that trends derived for indicators from the IRN are climate driven, but as yet cannot be attributed to anthropogenically induced climate change. Indeed, for summer means and low flows the results from observations were contrary to those projected from climate change impact assessments, which suggest large reductions in river flows (Charlton and Murphy, 2008; McGrath *et al*., 2008; Bastola *et al*., 2011c). The detection of anthropogenic climate change signals in river flow indicators at the catchment level is difficult given the low signal- (anthropogenic climate change) to-noise (year-to-year and multi-decadal variability) ratio within hydrological time series. In this section attention is moved to estimating *when* and *where* climate change signals are likely to be detected in the IRN, using current methods of trend analysis. Such information is important for informing current and future water resource and flood management in adapting to climate-driven changes.

A number of investigations in recent years have examined the approximate time expected for projected changes in river flows and precipitation to become detectable (e.g. Ziegler *et al*., 2005; Wilby, 2006; Fowler and Wilby, 2010; Murphy *et al.,* 2011). Estimates using data for river basins in the USA and UK suggest that statistically robust, climate-driven trends in annual and seasonal runoff are unlikely to be found until the second half of the twenty-first century at the earliest (Ziegler *et al*., 2005; Wilby, 2006). While long detection times are apparent, these studies have highlighted the importance of more careful selection of indicators for analysis in order to reduce detection times and the possibility of identifying sentinel stations within observational networks that may be 'early bird' stations in detecting climate change signals. The identification of indicators and stations for early detection and estimation of the time (in years) needed to detect climate change offers potential for focusing climate change monitoring and detection and in addition for developing policy for anticipatory adaptation. The work presented here follows the methodology established by Ziegler *et al*. (2005), Wilby (2006) and Fowler and Wilby (2010).

Two tasks were performed:

1 Calculation of the *strength of trend* (percent change) needed in order for a linear trend to be statistically detectable under widely used significance levels for individual indicators and catchments by 2025 (representative of 2020s) and 2055 (representative of 2050s);

2 Estimation of *detection times* (in years) for future climate change signals to become statistically detectable.

4.2 Methods Employed

The number of years of record required to detect a statistically significant trend depends on a number of factors, including: the strength of trend, the variance of the time series, the probability of Type I error (false trend detected when none exists) and the probability of Type II error (failure to detect a trend when one is present). Errors of Type I can be addressed by setting the probability of erroneous detection (α) at a predetermined level of significance. At the 5 percent significance level there remains a 5 percent chance of erroneous detection. The probability of making a Type II error (1−β) depends on the power of the statistical test, which can be related to its ability to detect a specified trend at the required confidence level α (i.e. its ability to detect an alternative hypothesis), and varies with record length, trend magnitude and the distribution of the time series.

Ziegler *et al*. (2005) relate the number of years (y_{detect}) of data (counted from 1990) needed to detect a linear trend (τ) for a specified α and β in the equation (Eq. 4.1):

$$y_{detect} = \left[\frac{12\sigma^2}{\tau^2}\left(W_{1-\frac{\alpha}{2}} - W_\beta\right)^2\right]^{\frac{1}{3}} \qquad \text{Equation 4.1}$$

where $W_{1-\alpha/2}$ and W_β are the normal deviates at cumulative probability 1- α/2 and β respectively, and σ^2 is the sample variance of the observed time series. Here, estimates of σ^2 were taken from river flow time series for the period 1976–1990.

Initially, for Task 1 a conservative approach was taken towards committing Type I and II errors with the significance level required for detection set at α = 0.05 (5 percent significance level) and the power of the statistical test β = 0.1 respectively. For Task 2, a broad range of linear changes in annual and seasonal mean flows were employed (between 5 and 50 percent over the investigated period) to represent possible trends for future climate change impacts.

For Task 1, following Wilby (2006), Eq. 4.1 was rearranged to determine the strength of trend (percent change) needed for detection by 2025 (2020s) and 2055 (2050s). The magnitude of trend (τ) needed in order to be detectable by a given time period is shown in Eq. 4.2:

$$\tau = \left[\frac{\left(W_{1-\frac{\alpha}{2}} - W_{\beta} \right)^2}{y_{detect}{}^3} 12\sigma^2 \right]^{\frac{1}{2}} \qquad \text{Equation 4.2}$$

The same parameters as described for Eq. 4.1 were used. To estimate the years required to detect linear trends and the magnitude of change required for detection by the 2020s and 2050s for selected flow indicators, Eqs 4.1 and 4.2 were applied to all 37 stations in the analysis for the standard period 1976–2009. The indicators examined were the annual and seasonal mean flows and the MAX10 high flow.

4.3 Results

4.3.1 Change required for Detection of Trends in Flow by the 2020s and 2050s

Figure 4.1 shows the percent change in flow indicators required for detection by the 2020s and the 2050s. The thick black line represents the median change required for detection across the IRN, with estimates based on a sample variance from 1976–2009. In terms of median results across the network, annual mean flows must change by 32 percent by 2025, or 23 percent by 2055, to be detectable at the 5 percent significance level. These estimates increased to 38 percent and 28 percent respectively when sample variance was taken from eight long record stations from 1955–1990 (not shown here). This increase is reflective of the larger variance associated with longer records. Changes required for detection were greater for seasonal mean flows. A change of 43 percent (2020s) or 31 percent (2050s) was needed for detection in winter mean flows. Similar magnitudes of change were required for spring mean flows. Required changes were considerably larger for autumn (63 percent by 2020s) and largest for summer (123 percent by 2020s or 90 percent by 2050s). For each indicator analysed the change required for detection was in excess of the ranges of change projected from climate change impact assessments for each future time period (Murphy and Charlton, 2008; Steele-Dunne *et al.*, 2008).

There was considerable variation in the amount of change required for detection among individual stations and indicators, confirming the potential for identifying sentinel sites and indicators for climate change detection within the IRN. The range between the lowest and highest degree of change needed for detection was largest for summer mean flows. Stations around the upper Shannon basin showed changes that will potentially be statistically detectable by the 2050s in both winter and spring. The lowest detectable trend was found in winter mean flow for St26021 (River Inny at Ballymahon) in the Shannon RBD. The change needed for detection at the 5 percent significance level is 23 percent by 2025, or 17 percent by 2055, with the latter within the upper range of changes projected for this catchment by mid-century (Murphy and Charlton, 2008; Steele-Dunne *et al.*, 2008).

Representative of high flows, the magnitude of change required for detection in MAX10 day flows was also calculated. Evident from Fig. 4.1 is that the median change across stations required for statistical detection is 42 percent by the 2020s or 31 percent by the 2050s. However, an important distinction is that changes in future high flows are likely to be considerably larger than in annual means. With a stronger trend in high flows, combined with a relatively low amount of change required for detection, high-flow indicators are likely to have a greater probability of revealing statistically significant trends.

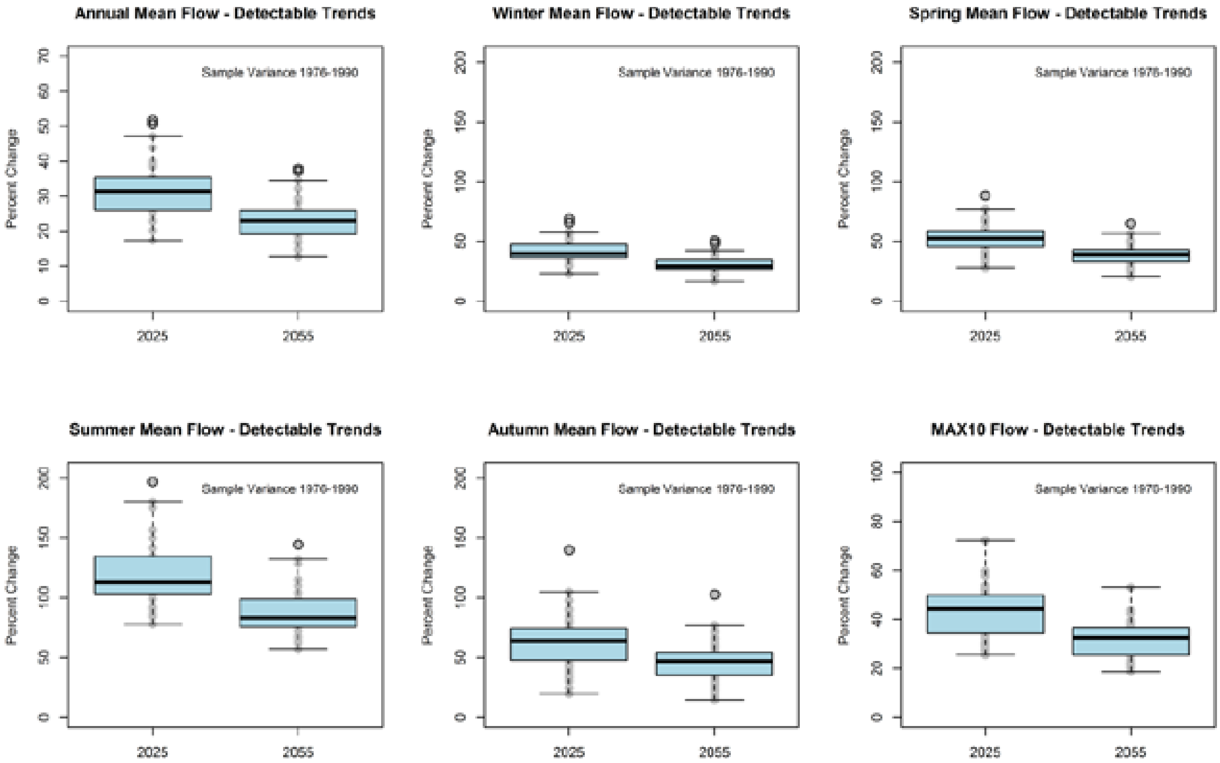

Figure 4.1. Box and whisker plots showing the magnitude of change (percent) required for trends to be detectable at the 5 percent significance level for annual, seasonal mean and MAX10 river flow by the 2020s (2025) and 2050s (2055). Sample variance is derived for the period 1976–1990. Grey dots represent each station.

4.3.2 Detection Time Estimates for Changing Trend Magnitudes

Ideally, for estimating the time needed for detection of climate change signals, ranges of projected time series of future river flows would be employed. However, such simulations have only been produced for a small number of stations in the IRN to date. To overcome this, detection times were calculated for changes taken as representative of the range of changes from impact assessments conducted for Irish catchments. Here the number of years (from 1990) required to statistically detect hypothetical future changes in flow for the 2020s and 2050s were estimated, with changes ranging between 5 and 50 percent.

From Fig. 4.2 approximately 60 years (from 1990) would be needed to detect a 15 percent change in annual mean flow by the 2020s, meaning that it would not actually be statistically detected in observations at the 5 percent level until mid-century. Trends in summer mean flows are the least detectable, with 140 years on average required to detect a projected 15 percent change by the 2020s. Larger magnitudes of change for summer take considerably less time to detect, with one station taking less than 50 years (from 1990) for a 45 percent change in summer mean flows to emerge as statistically significant at the 5 percent level.

A number of studies in Ireland have modelled river flows under plausible future climate change scenarios

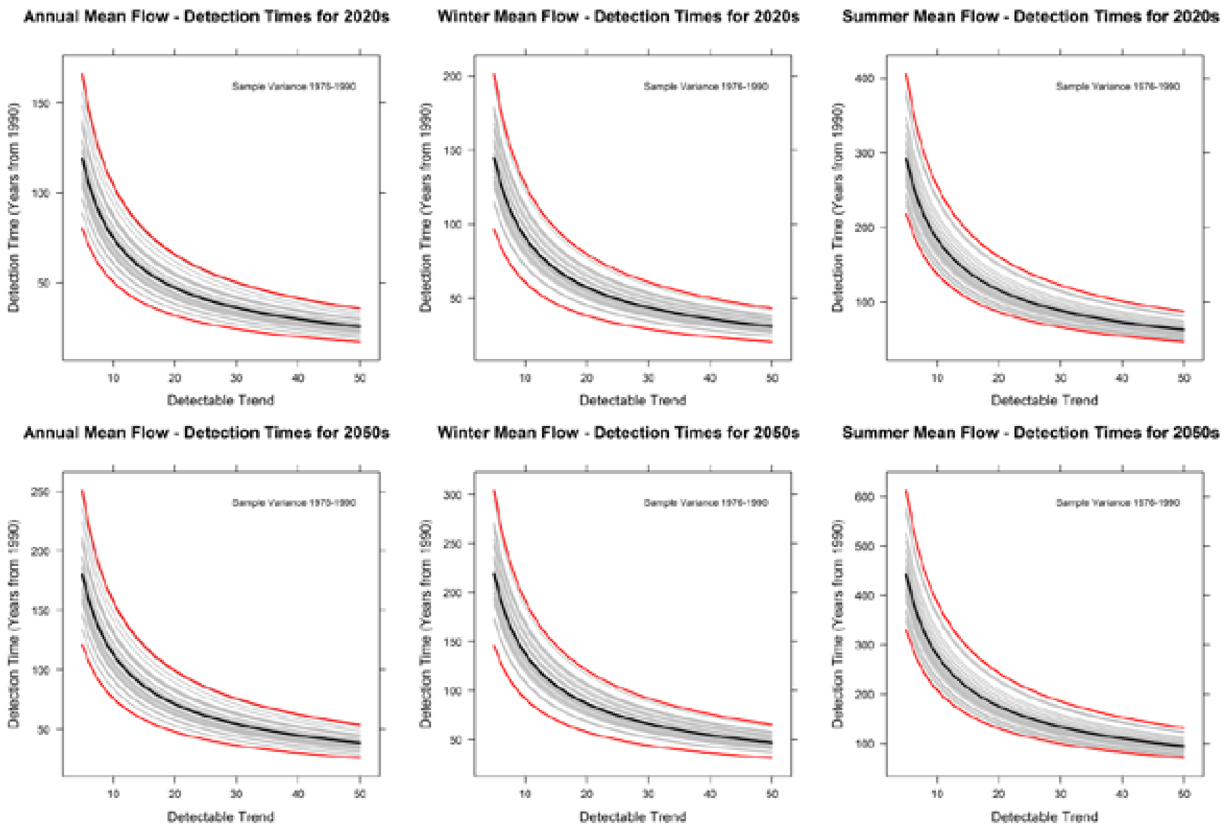

Figure 4.2. Detection time (in years from 1990) with varying trend magnitudes ranging from 5 to 50 percent in annual, winter and summer mean flow by the 2020s (top) and 2050s (bottom) for the sample variance (1976–1990) and a 5 percent significance level. Grey lines represent each catchment's detection time, black line is the mean detection time across the network and red lines represent the min and max.

to assess the potential effects of climate change on hydrology. If realised, these impacts would have significant negative societal, ecological and economic effects. Taking a number of these studies in Ireland, the time required for detection was estimated. Winter mean flow in the Suir and Barrow catchments is projected to increase between 15 and 20 percent by the 2050s (Murphy and Charlton, 2008). It would be after the 2080s before this magnitude of trend would become evident in observations in the majority of stations analysed in the present study: however, for St26021 in the Shannon basin this change would be detectable before the 2050s. Steele-Dunne *et al*. (2008) suggest decreases in summer mean flow ranging between 20 and 60 percent, with an approximate median change of 40 percent for nine study catchments by mid-century. For 40 percent decreases in summer mean flow a wide range of detection times are evident. However, some sites showed that changes in summer mean may be statistically detectable by the 2060s, but only if the more extreme scenarios are realised.

4.4 Sentinel Sites and Early-detection Indicators

There was a considerable difference between stations and indicators in terms of the time taken to statistically detect climate change signals and the magnitude of change required for detection. As noted by Wilby (2006), the coefficient of variation (CV = standard deviation divided by mean) may be used as a simple diagnostic of how detectable trends in hydro-climatic variables may be for individual basins. The CV is a normalised measure of dispersion, and shows the extent of variability in relation to the mean and is easily calculated. The general premise is that stations with low CVs have a lower noise and may provide earlier detection times of climate change signals, as they have a higher signal-to-noise ratio. To investigate if this relationship is held for Irish catchments, the correlation between each catchment's CV (calculated from the time series of each indicator per catchment from 1976–2009) and the percent change needed for statistically

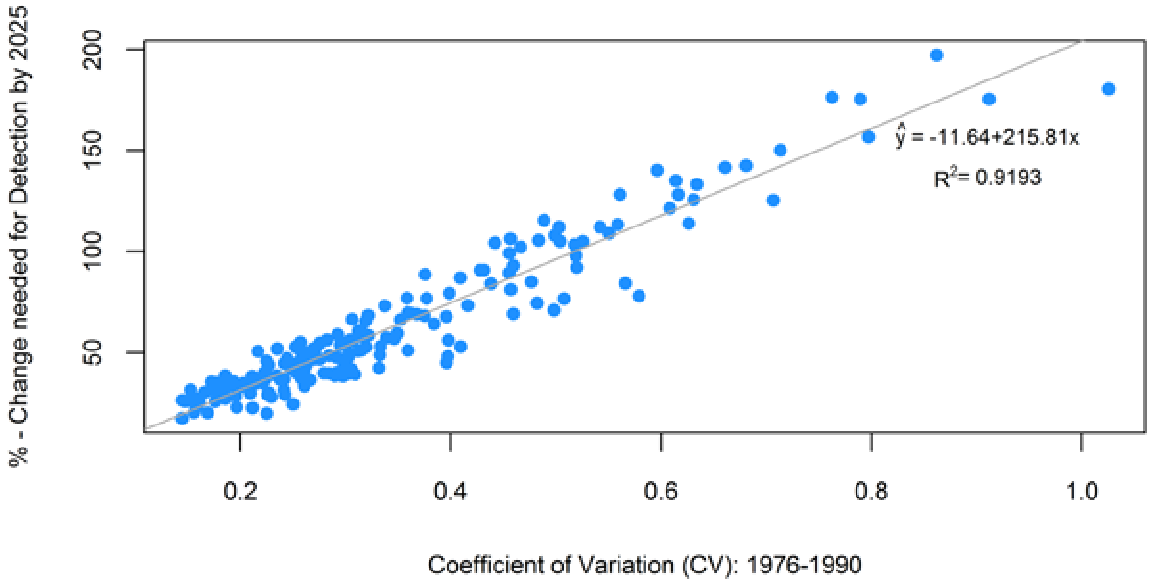

Figure 4.3. Correlation of the percent change needed for statistically significant detection by mid-2020s (2025) with the coefficient of variation (CV) from 1976–2009 for annual and seasonal mean and MAX10 flow indicators (α=0.05). The fitted regression model line, equation and R^2 are displayed.

significant detection by the 2020s (and 2050s, not shown here) was assessed for annual and seasonal mean flows and MAX10 indicators.

From Fig. 4.3 a very strong positive correlation is evident (Spearman's rank correlation coefficient, r = 0.937 with n = 185). In addition, a simple least-squares regression model was fitted between CV (predictor) and percent change needed for detection (= -11.64 + 215.81(CV) with R^2 = 0.9193; n = 185). In this linear model almost 92 percent of the variation in the response was explained by the CV. The lower an individual catchment's CV for a particular indicator, the lower the percent change needed for statistical detection. This relationship makes sense as the CV is the inverse of the signal-to-noise ratio. Stations with low CVs had lower noise and this makes detection of the underlying signal (here climate change), much more likely and earlier. Therefore, stations showing a low CV were found to be more likely to be sentinel sites for an indicator of interest. Additionally, the choice of indicator used for analysing trends also influenced the detection times required with some indicators showing considerably more variance on average than others in the observed series.

A summary of mean CV for all 22 indicators across all of the IRN stations is shown in Fig. 4.4 for the period 1976–2009. There is a large difference in the mean CV between indicators. Based on these summaries and the positive relationship in Fig. 4.3 it can be inferred that indicators showing low average CVs, and thereby increased detectability, include the annual mean flow, MAX10, MAX30 and IAMAX. Indicators with high CV and therefore decreased detectability include summer mean flows, MIN7, and the seasonality indicator (SE).

In spite of long detection times, with a greater understanding of what governs or hampers the detection of change within river flow records opportunities arise for identifying sentinel indicators and stations. Timely detection of climate change signals would be possible for records with a high signal-to-noise ratio in hydro-climatic time series. This has been shown here whereby the careful selection of indicators with low CVs and the further identification of individual stations with low CVs within observational networks increase the detectability of climate change signals. It is also important to combine this information with the magnitude of future projected change. For annual mean flows, while CV

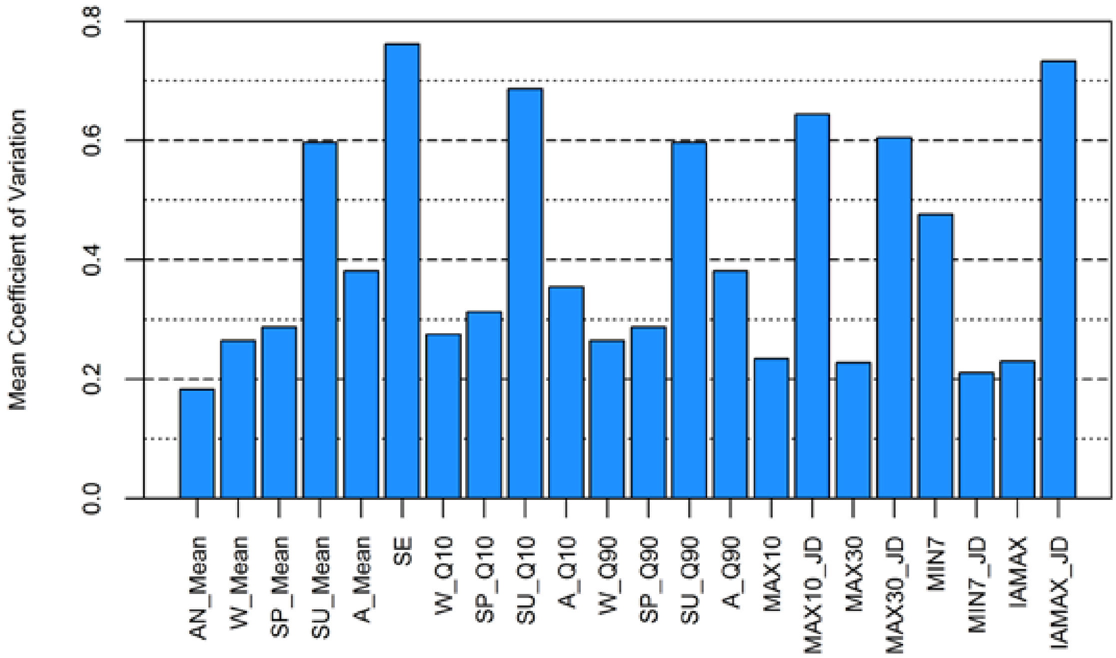

Figure 4.4. Mean coefficients of variations (CVs) for individual indicators for stations in the Irish Reference Network (IRN). CVs are estimated from the period 1976–2009.

was low, the projected magnitude of change in annual means is unlikely to be large enough for early detection in this indicator. Extreme and extended duration high-flow indicators: IAMAX, MAX10 and MAX30 showed the greatest potential for being early detection indicators; combining low CV with the likelihood of greater magnitude (stronger trend) for future impacts, providing that future CV of these indicators do not increase with potential future changes. Interestingly, from the analysis of observed trends in Section 3 these indicators also showed the most evidence of persistent increasing trends across the majority of stations.

4.5 Discussion and Conclusions

There is a high risk of interpreting the absence of statistically significant trends as absence of underlying change. This is categorically not the case. There is considerable evidence that anthropogenic changes in climate due to increases in greenhouse gases have had a direct effect on the observed global water cycle over the last 50 years (Gedney *et al*., 2006; Huntington, 2006; IPCC, 2007; Barnett *et al.,* 2008). Detection of climate-driven trends at regional scales is more problematic due to high inter-annual and decadal variability of river flows (Burn and Hag Elnur, 2002; Wilby, 2006; Fowler and Wilby, 2010). Using current trend analysis approaches (assuming a linear trend) and conservative statistical criteria, projected changes in annual and seasonal river flows are unlikely to be detected by mid-century. This has been the case in other countries (Ziegler *et al*., 2005; Wilby, 2006; Fowler and Wilby, 2010) and is driven by the difficulty in detecting low signal-to-noise changes at a high statistical significance level. Such findings increase the importance of monitoring for climate change to track the emergence of signals relative to natural variability, and to provide information for validating output from climate change impact assessments without solely relying on statistical significance.

The detection of signals of change is most difficult for seasonal mean flows – especially summer, given the large amounts of inter-annual and multi-decadal variability in these variables. The analysis of flows in the IRN confirms this with few significant trends identified. High flows, on the other hand, show greater potential for early detection of climate change signals. This agrees with the findings of Frei and Schär (2001) for precipitation who highlight that extreme events are likely to be more robustly detectable than changes in the mean, as with atmospheric warming the water-holding capacity of the atmosphere is likely to increase leading to a greater proportion of rainfall occurring as heavy events. Fowler and Wilby (2010) suggest that this may increase the signal-to-noise ratio and enable more robust detection of changes in extreme events.

The approach taken here employed a conservative approach to trend detection. The probability of Type I errors, α, was set at 0.05 and the probability of Type II errors set at 0.10. The level of statistical significance required for trend detection can have a large bearing on the results. Radziejewski and Kundzewicz (2004) show that to detect changes at the 1 percent significance level, the magnitude of change must be at least 44 percent greater than is the case at the 5 percent level.

Figure 4.5 shows for an example station that when the statistical 'strictness' is decreased (i.e. increased values of α and β) the magnitude of change needed for statistically significant detection also decreases considerably. Therefore, 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, they may have profound effects on vulnerable water resources or communities exposed to flood risk (McCabe and Wolock, 2002). Further research and discussion is needed to identify at what levels (thresholds) trends may become practically significant. This is likely to vary depending on the vulnerability of exposed communities and water systems to projected changes.

The work presented here has highlighted the potential for identifying sentinel sites and indicators within the IRN for early detection of climate-driven change signals. By judiciously selecting stations and indicators with low CV there is a possibility of zoning in on 'sentinel' climate change monitoring areas (catchment types within the IRN). However, it is important to avoid bias in monitoring and analysis strategies by focusing on certain areas and indicators to the detriment of others. Although signals in high flows may emerge first, changes in high CV indicators, particularly low flows, are important to water resource management and the aquatic environment. As mentioned above, identifying thresholds of change

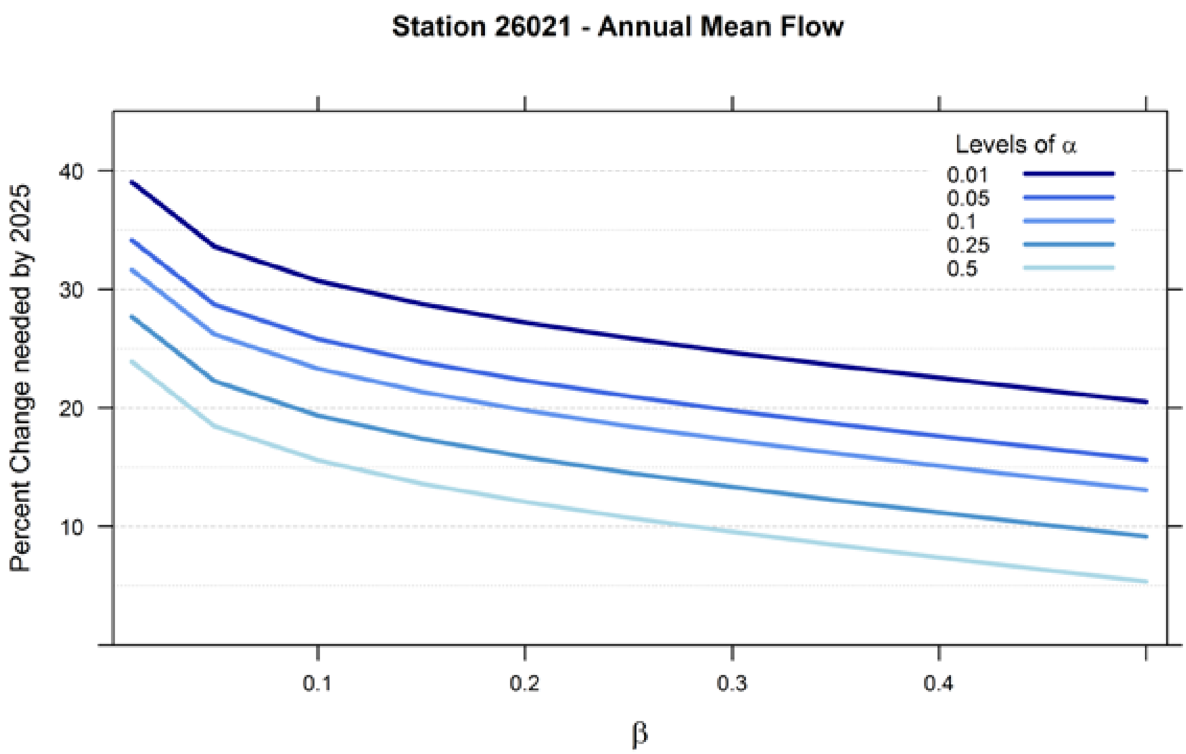

Figure 4.5. Estimated percent change needed for detection of linear trends by 2020s (2025) for varying α and β (parameters in Equation 1 and 2) for station 26021 annual mean flow (variance: 1976–2009).

related to practical significance (where changes have a real impact on sustainable use of resources and other management decisions), rather than relying on statistical significance, should be a priority for both future water research and management.

In terms of adaptation planning, it is important to note that waiting for unequivocal statistical proof of climate change signals within hydrological series, at conservative statistical levels, before instituting adaptation policies may turn out to be excessively detrimental where vulnerability to change is high (Ziegler *et al*., 2005). For the foreseeable future, water managers will have to make climate change adaptation decisions in advance of formally detected changes. Robust and scenario-neutral approaches to adaptation that are based on understanding the sensitivity of individual catchments to change, minimising current vulnerability to climate change and the stress-testing of decisions against the range of possible impacts have been highlighted in the literature (Wilby and Dessai, 2010; Prudhomme *et al.*, 2010; Bastola *et al.*, 2011b; Hall and Murphy, 2011; Hall *et al.*, 2012) and offer considerable potential.

These findings heighten the importance for reference hydrometric networks for monitoring and detecting climate change signals at the catchment scale. With a stronger climate change signal over time the likelihood of detection may grow, even where changes have not yet been detected, they may be detected in future (Radziejewski and Kundzewicz, 2004). In addition, large assumptions are made in the approach adopted here. For example, it is assumed that climate change will be manifested as a gradual, linear change over time. This may not be the case and change may occur suddenly as a step change in time series.

It is fundamental that monitoring is carried out to track the development of climate-driven changes over time to better understand the nature of changes and to inform adaptation policies. It will also be important to have series of observed river flow indicators, that are free from confounding factors for verifying the simulations produced from Global Climate Models and for training hydrological impact models for informing adaptation planning. In addition, the possibility of identifying sentinel stations increases the ability to more effectively optimise the deployment of resources for monitoring climate-driven change in hydrological records. In spite of this, fundamental research is simultaneously needed to explore approaches for improving the detectability of change signals in hydro-climatic time series.

5 Reconstructing River Flow Records

5.1 Introduction

During the selection of stations for inclusion in the IRN, a number of sites were identified that had long records but were punctuated with large amounts of missing data, or had been heavily influenced by arterial drainage. Given the importance of long records in contextualising results from shorter duration series, attention was given to reconstructing river flows rather than omitting these potentially valuable stations from the analysis. In addition, where the availability of longer precipitation and evapotranspiration data allowed, river flow series were also extended in time. This section details the results of this reconstruction process.

In total five stations were reconstructed in this work. Most important is the Boyne at Slane Castle (St07012). This station has a long, high-quality digitised record. However, the catchment has been heavily impacted by arterial drainage over an extended period of time. While the post-drainage period was included in the final reference network, effort was made here to make use of the pre-drainage record to reconstruct annual and seasonal mean flows up to present to exclude the influence of arterial drainage.

Three further stations with large amounts of missing data were also reconstructed with the aim of rescuing as much information as possible from the available series. These stations include the Avonmore at Rathdrum (St10002), the Flesk at Flesk Bridge (St22006) and the Kilmastulla at Coole (St25044). One final station, Ballysadare at Ballysadare (St35005), was also included. While this station is already part of the reference network, it has a number of consecutive years missing and the proximity of Markree Castle (one of the longest recording rainfall stations in the country) offered the potential to extend the record for this station back in time. Figure 5.1 displays the percentage of missing daily mean flow values per month for these four stations. While there is valuable data available it is obvious that these observed time series are effectively 'broken' for the purposes of trend analysis. The longest records within the IRN commence in the 1950s, therefore the time-consuming process of reconstructing these stations was worthwhile in extending the available time series lengths for analysis.

5.2 Reconstructing River Flows

5.2.1 Rainfall Runoff Model Selection

Conceptual rainfall runoff (CRR) models were employed for reconstructing river flows for the above time series. Conceptual rainfall runoff models use mathematical equations to conceptualise and aggregate the complex, spatially distributed, and highly interrelated water, energy, and vegetation processes in a watershed, to simulate river flow. Due to the randomness in nature and the lack of complete knowledge of the hydrological system, uncertainty is an unavoidable element in any hydrologic modelling study (Beven, 2002; Gupta *et al*., 2003). In hydrological modelling, uncertainty stems from a variety of sources such as: data uncertainty, parameter uncertainty, model structural uncertainty and state uncertainty (Bastola *et al*., 2011a; 2011d). From among the large number of models that can be used for the purpose of modelling flow in catchments, three conceptual rainfall–runoff models were assessed:

NAM: a conceptual lumped rainfall–runoff model which was originally developed at the Institute of Hydrodynamics and Hydraulic Engineering at the Technical University of Denmark. The detail on the parameters and more detailed information regarding the NAM model can be found in Madsen (2000).

The Hydrologic MODel (HyMOD): also a conceptual and lumped model. Developed to provide a research tool for scientific-evaluation purposes (e.g. Wagener *et al*., 2001).

HYdrological SImulation Model (HYSIM): is a conceptual rainfall-runoff model, which uses rainfall and potential evaporation data to simulate river flow using parameters for hydrology and hydraulics that define the river basin and channels in a realistic way (Manley, 2006).

Table 5.1. Comparison of hydrological model performance using the Nash Sutcliffe Efficiency Criterion (NSE) for the Boyne at Slane Castle.

Model	Calibration 1942–1960	Validation 1961–1969
HyMOD	0.909	0.900
NAM	0.869	0.862
HYSIM	0.919	0.934

Each model was calibrated and validated for the Boyne catchment. The optimum performance of each model was assessed using the Nash Sutcliffe Efficiency (NSE) criterion, which is widely used for assessing model performance in the literature. A value of 1 for NSE represents a perfect model fit. NSE scores for each model for calibration and validation are provided in Table 5.1 for the Boyne at Slane Castle (St07012), with results based on daily data. Despite differences in model structure and complexity, similar results were obtained for each model. From Table 5.1 the HYSIM model shows the best performance in both calibration and validation in terms of the NSE criteria and was chosen for further use in reconstructing river flows.

5.2.2 *Model Calibration and Validation*

In reconstructing annual and seasonal flows for each catchment, daily rainfall records for stations within each catchment were obtained from Met Éireann and averaged to derive catchment-average precipitation. Table 5.2 shows the rainfall stations used for each catchment. Daily potential evapotranspiration data was obtained from the closest synoptic station in each case. For each catchment, calibration and validation periods were established, with calibration years selected to train the model on as much hydrological variability as possible. Calibration was undertaken

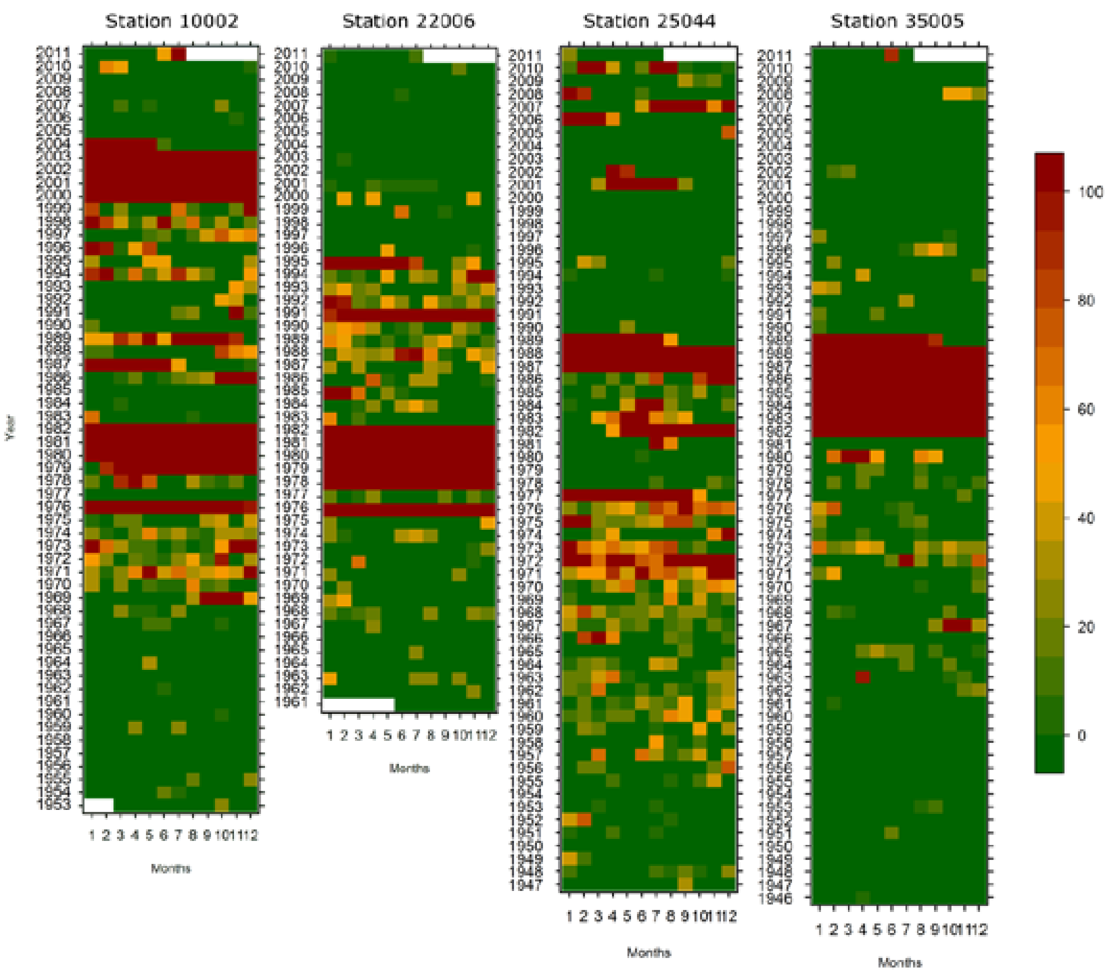

Figure 5.1. Missing value plots showing the percent of daily flows missing from each month for selected stations.

at a daily time step by optimising the value of the selected objective function, NSE. Modelling results presented here are based on optimised values of model parameters for HYSIM.

Table 5.3 shows the periods selected for calibration and validation for each station along with NSE values for daily and monthly simulations. Highest results are obtained for St07012 and St35005 for both calibration and validation. Figure 5.2 shows the observed and modelled monthly mean flows along with a scatter plot comparing the observed and reconstructed flows for each station. The plots highlight the overall skill of the model in simulating the range of monthly mean flows for each catchment. It must be noted that whilst the NSE is one of the most commonly used efficiency criteria, and model performance was good, it is biased towards high flows (Krause *et al*., 2005) at the expense of low-flow simulation accuracy.

Table 5.2. Rainfall stations used for the generation of catchment average precipitation for each of the reconstructed river flow series.

River flow station	Rainfall station No.	Rainfall station name	Height
07012 Boyne at Slane Castle	331	Enfield	113
	431	Dunsany	71
	931	Kells	67
	1031	Athboy	87
	1731	Ballivor	68
	1931	Oldcastle	108
	2531	Navan	50
	2931	Warrenstown	90
10002 Avonmore at Rathdrum	520	Rathdrum	131
	620	Lough Dan	213
	720	Ballinastoe	396
	820	Moneystown	207
	1420	Glenmacnass	238
22006 Flesk at Flesk Bridge	505	Killarney	55
	605	Killarney	34
	1105	Killarney	32
	2505	Barraduff	113
	3205	Killarney	58
	9305	M. Torc	223
25044 Kilmastulla at Coole	319	Killaloe	38
	1619	Birdhill	34
	2219	Dollag	86
	4019	Rearcross	210
	4719	Newport	180
	4819	Silvermines	312
	5419	Newport	61
35005 Ballysadare at Ballysadare	636	Markree Castle	39
	936	Coolaney	65
	1236	Gurteen G	73
	1736	Ballintog	66
	1836	Ballymote	79
	2636	Lough Gill	15

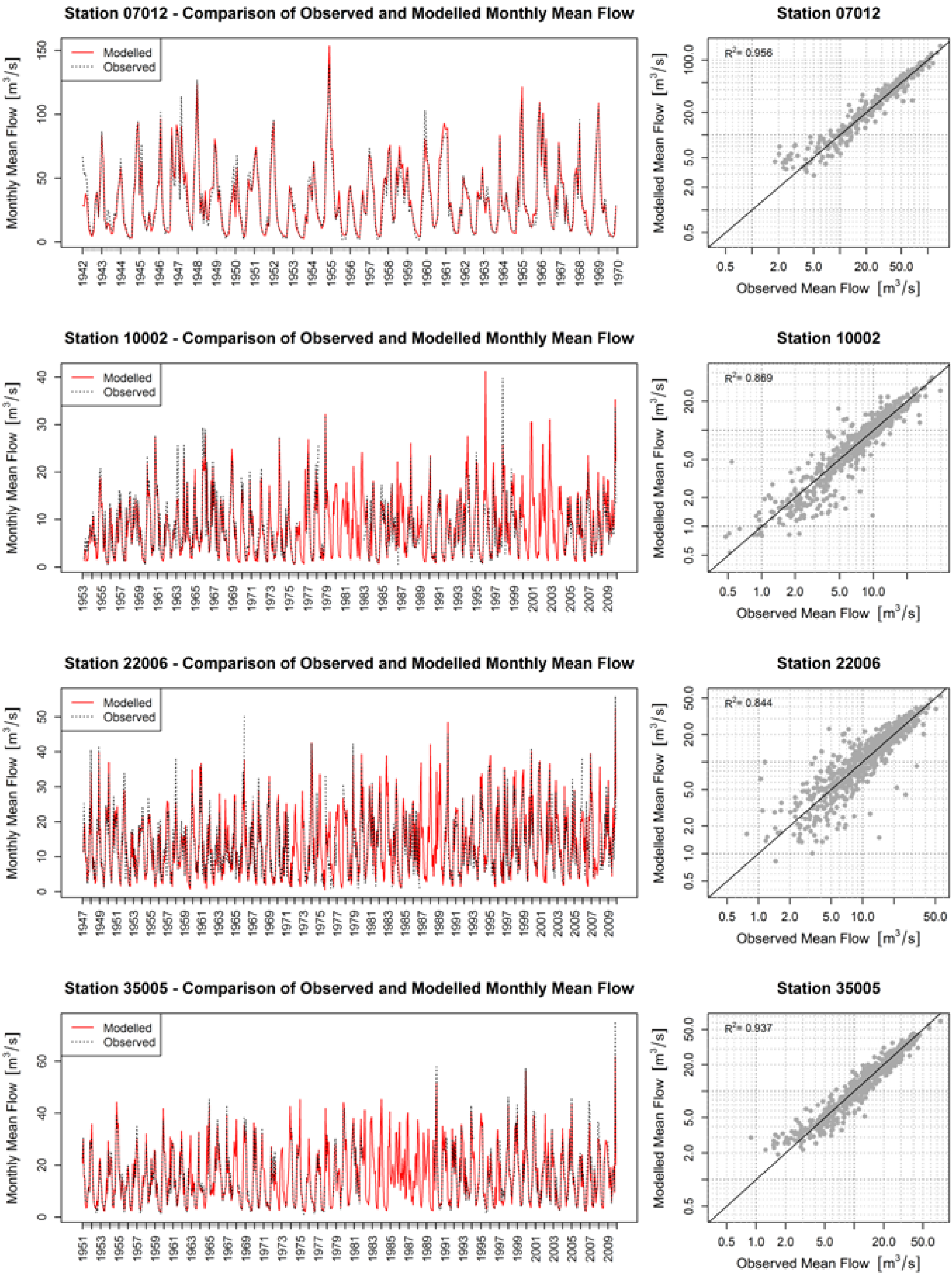

Figure 5.2. Calibration and validation results for each reconstructed catchment. Plots on the left represent the monthly flow regime for simulated and observed flow, while the scatter plots show a comparison of monthly simulated and observed on log scale.

Table 5.3. Calibration and validation dates and model performance at daily and monthly timesteps for each catchment. NSE is Nash Sutcliffe Efficency criterion – for which a perfect fit gives a value of 1.

	Calibration			Validation		
Station	***Dates***	***NSE Daily***	***NSE Monthly***	***Dates***	***NSE Daily***	***NSE Monthly***
07012	1944–1960	0.919	0.960	1961–1969	0.934	0.977
10002	1990–2009	0.790	0.915	1953–1989	0.774	0.882
22006	1947–1989	0.727	0.831	1990–2009	0.742	0.861
25044	1990–2009	0.778	0.847	1961–1989	0.776	0.823
35005	1950–1980	0.882	0.911	1990–2009	0.864	0.930

5.3 Trend Analysis of Reconstructed Series

In order to assess trends in reconstructed and extended series the moving windows approach, based on alternating start and end years of analysis and further detailed in Section 3 was employed to explore trends for all possible combination of years of minimum 10 years' duration. Results are presented based on reason for reconstruction, i.e. arterial drainage or missing data. While significance of trends is presented, care should be taken here as serial correlation of the series is not assessed for the reconstructed flows. In this section, of most interest is assessing the direction and magnitude of variability and change within these reconstructed series.

5.3.1 Arterial Drainage – the Boyne at Slane Castle (St07012)

Within the Irish context, arterial drainage is a key confounding factor for trend analysis, as drainage changes the flow regime. Historically, in response to issues such as inadequate drainage and frequent flooding, a large number of catchments in Ireland have been subjected to extensive drainage schemes, which became more widespread following the Arterial Drainage Act of 1945. For the greatest part, the concentration of such schemes is on the deepening and widening of the river channels (Bhattarai and O'Connor, 2004) to facilitate field drainage in increasing agricultural productivity of surrounding lands. Following drainage, there is an acceleration of the hydrological response to rainfall, with flood peaks of increased intensity and more rapid hydrograph recessions (Lynn, 1981). In addition to impacts on flood flows, Essery and Wilcock (1990) found that low flows were increased following arterial drainage of the upper River Maine in Northern Ireland. Such changes in hydrological response have a significant confounding effect on trend analysis.

The Boyne at Slane Castle is the longest continuous and digitised record in Ireland with over 70 years of daily data. As part of the recent FSU the station was categorised as 'A1' – the highest ranking for the quality of the rating curve at high flows. In addition, only 0.39 percent of the record is missing for the purpose of trend analysis. However, the catchment was subject to extensive arterial drainage during 1969–1986. Figure 5.3 shows the extent of arterial drainage, including channels affected and areas of benefitting lands. The reconstruction process for St07012 is distinct from other stations considered here, where the emphasis is on understanding how trends would have evolved in the absence of arterial drainage rather than on reconstructing the record due to missing data. For this purpose calibration and validation was carried out for the pre-drainage record and used to simulate flows during and post-drainage. Table 5.3 outlines the calibration and validation dates used. All models, particularly HYSIM, are successful at capturing the daily and monthly mean flows.

Simulations of annual mean flows from the three hydrological models and their combined median, for the entire period of record, are shown in Fig. 5.4. Evident is the fact that there is a large divergence between model simulated and observed flows in the post-drainage record from 1970 onwards, but particularly after 1980. After this point the models underestimate the observed annual mean flow. The uniform response of models gives confidence that this underestimation is not an artefact of one particular model. Investigation of the seasonal flows indicates that this increase in discharge post-drainage is largely derived from winter flows and is consistent with the impacts of arterial drainage observed in other studies. In plotting a linear trend through the record 1943–2009, there was a considerable difference between the trends obtained from observed (strong increasing trend) and reconstructed flows (flat dashed line). It is hypothesised that this divergence in trends is due to arterial drainage in the catchment over the period 1969–1986. The trends in the two series are fully explored in Fig. 5.5, which compares Mann-Kendall Zs values for alternating start and end years for the annual mean flows for both the observed and reconstructed series derived with HSYIM.

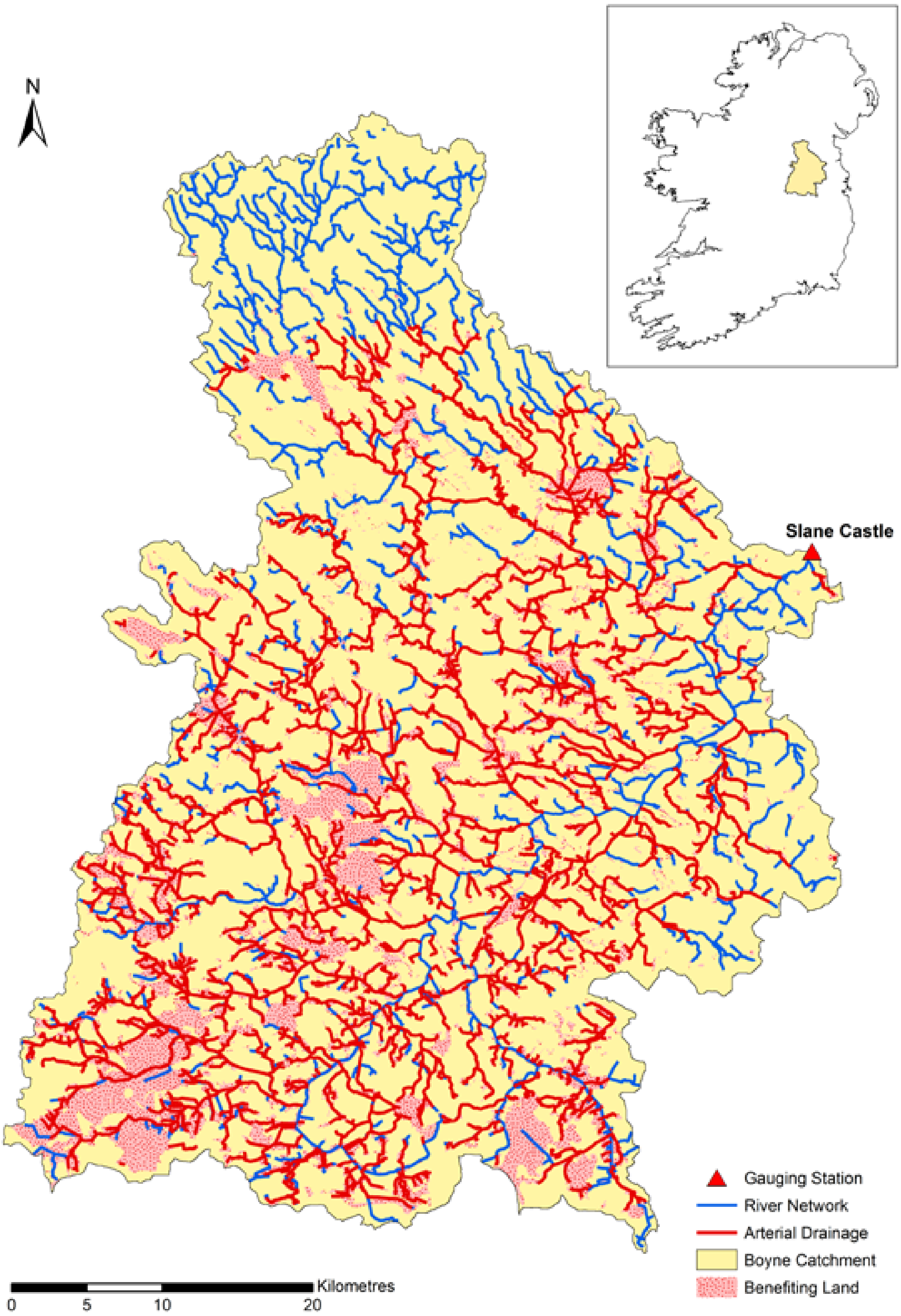

Figure 5.3. Extent of arterial drainage in the Boyne Catchment at Slane Castle showing channel schemes and benefiting lands.

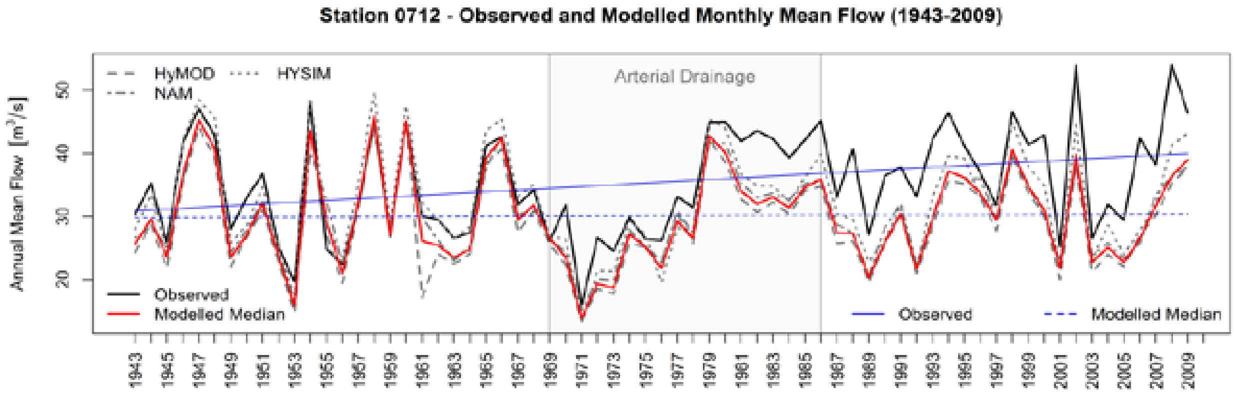

Figure 5.4. Observed and simulated flows from three rainfall runoff models and their combined median for the entire flow series for Slane Castle (1943–2009). Linear trends are shown for the observed and the model median time series. Arterial drainage in the catchment was carried out for the period 1969–1986 (shaded in grey).

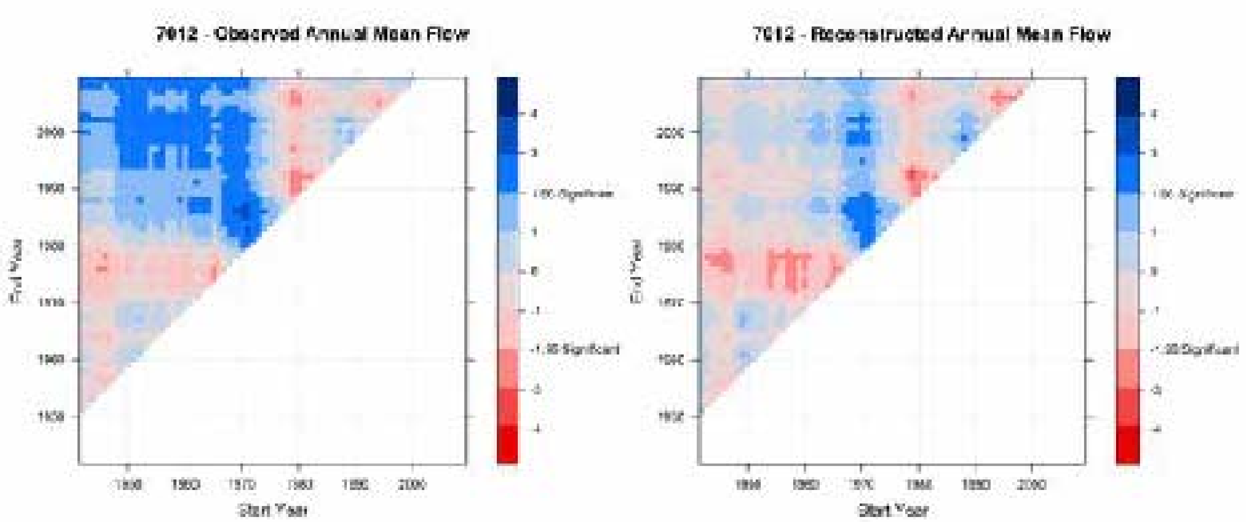

Figure 5.5. Moving windows analysis for trends in observed (left) and reconstructed (right) annual mean flow for the Boyne at Slane Castle. The plots show the Mann-Kendall Zs statistic for all possible combinations of start and end dates (minimum record length of ten years).Red (blue) signifies decreasing (increasing) trends. Significance is tested at 5 percent level with |MK Zs| > 1.96.

Evident from the comparison of trends derived from observed and reconstructed annual mean flows (Fig. 5.5) is that the shift towards strong significant increasing trends for records ending after the 1980s, which are evident in observed records, are not evident in the reconstructed flows which show only weak, non-significant trends for the same period. In addition, the similarities of trends derived for series commencing after the mid-1970s and for trend tests ending before the 1970s for both the observed and reconstructed series increase the confidence that the derived positive trends in observations are due to changes induced by arterial drainage. For the reconstructed flows the only significant trends identified are found for tests that begin in the late 1960s/early 1970s and can be associated with the dry conditions, particularly in the east coast around this time. There are also time periods for which significant decreasing trends are present in annual mean flows, particularly for series ending in the 1970s, but these are not persistent throughout the record.

Figure 5.6 explores trends in the reconstructed seasonal mean flows for the same station (St07012). In winter, weak decreasing trends are evident for the full period of record. For start years after 1950 weak increasing trends are evident, but the direction of trend is very much dependent on the period of record. Overall, there is a dearth of significant trends (increasing or decreasing) in winter mean flows across the entire series. There is evidence of a change point in spring mean flows for series beginning before the 1970s and ending after the 1980s. These increasing trends are significant at the 5 percent significance level until the end of the record where this significance has been lost. As in the analysis in Section 3, there is a considerable shift in the direction of spring flows, with trends derived from series commencing after 1960 showing non-significant increases, and becoming negative for records commencing after the mid-1970s.

Recent wet summers have had a strong influence on the direction and magnitude of trends (Fig. 5.6). For the long records, weak decreasing trends are evident for series ending between 1970 and 2000, after which the recent sequence of wet summers has seen the emergence of an increasing trend. Significant decreasing trends are evident for tests ending in the mid-1970s but are marked by extremes at the end of the record and do not persist. Conversely, tests beginning in the 1970s show significant increasing trends due to extreme drought conditions at the beginning of the record – emphasising again the influence of period of record for trend-analysis results. For autumn mean flows, long records

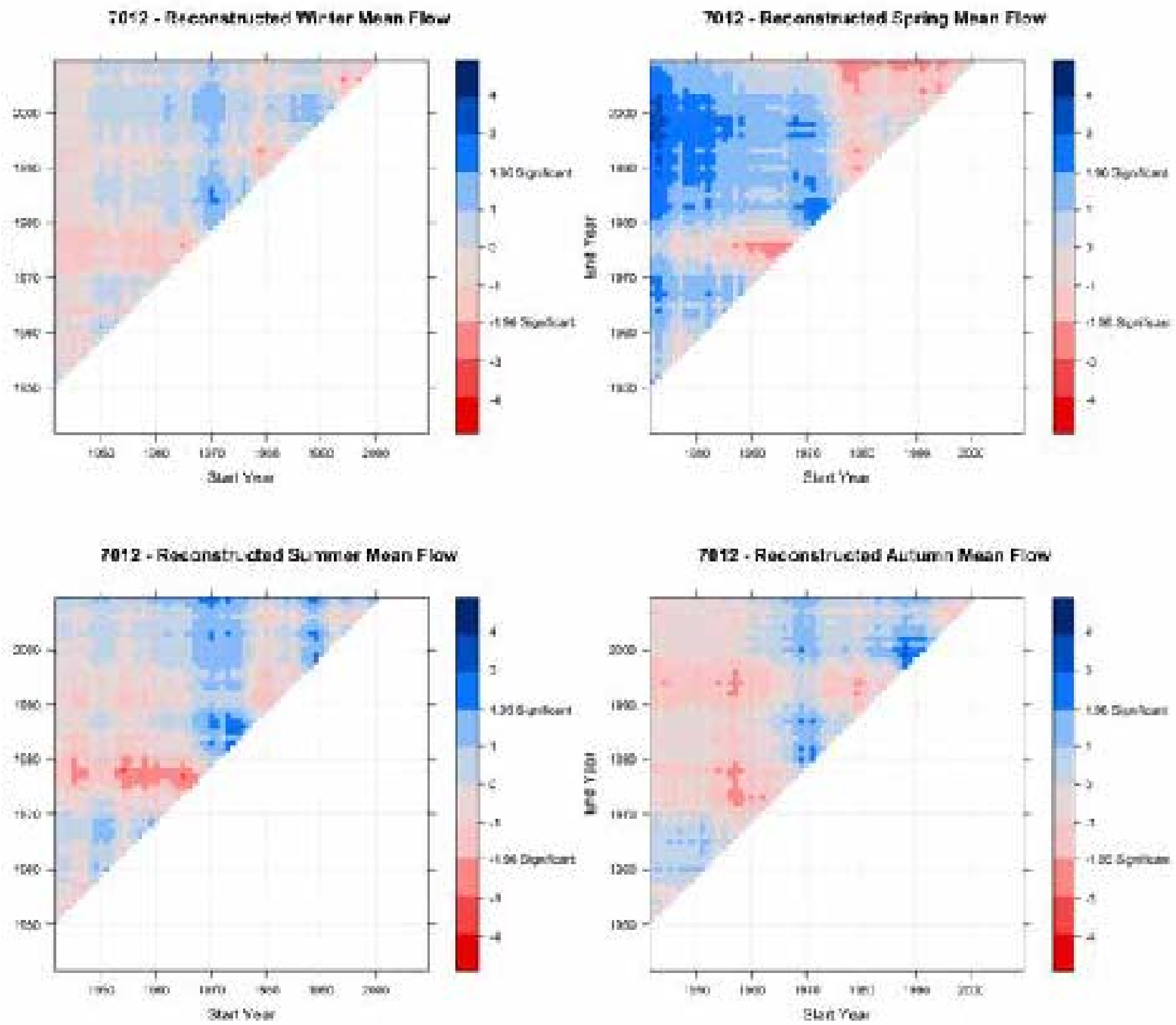

Figure 5.6. Moving windows analysis for reconstructed seasonal mean flows for the Boyne at Slane Castle. The plots show the Mann-Kendall Zs statistic for all possible combinations of start and end dates (minimum record length of ten years). Red (blue) signifies decreasing (increasing) trends. Significance is tested at 5 percent level with |MK Zs| > 1.96.

beginning before the 1970s tend to show decreasing trends, whereas those beginning after the 1970s show a tendency towards increasing trends. Again, there is a dearth of significant trends, with the exception of some very short records.

These results for the Boyne at Slane Castle are of note for a number of reasons. Firstly the long records that are available – back to 1941 – are the longest digitised records available in Ireland and are crucial in contextualising trends from shorter series, particularly in the eastern region of the country. Without reconstruction, the extent of arterial drainage that has taken place in this catchment would have rendered this valuable station unusable for long-term trend analysis, with the loss of over 40 years of data. Secondly, the Boyne at Slane Castle has been used to illustrate the change point in the mid-1970s that has been identified in the NAO and its influence on river flow in Ireland (Kiely, 1999). While this is undoubtedly a strong feature of Irish trends, the results presented here indicate that the change point identified for annual mean flows for this station by Kiely (1999) is at least partly explained by arterial drainage. While there is evidence of a change point in spring mean flows, and particularly in March (not shown here), the level of statistical significance is considerably less than that reported in previous research. These findings highlight the importance of metadata for understanding drivers of hydrological change, and exemplify the difficulties of attributing trends in hydrological indicators when there are multiple drivers at play, both internal and external to the catchment.

5.3.2 *Missing Data and 'Broken Records'*

Trend results for reconstructions of annual mean flows for stations adversely affected by large amounts of missing data are presented in Fig. 5.7. In addition to reconstructing the 'broken' flow series, monthly discharge for three stations was extended back in time. St22006 was extended from 1948 back to 1942, St35005 from 1946 to 1942 and St25044 to 1942 from 1961, adding almost 20 years of reconstructed data to the time series. It should be noted that the time series for St10002 could not be extended as far as the other time series using the hydrological modelling approach, due to shorter input series.

It should be borne in mind that these are reconstructed flows based on hydrological model output and so should be treated with caution because of associated modelling uncertainties. Nonetheless, they are useful for contextualising previously obtained trend results. For each of the reconstructed series, the analysis of annual mean flows showed a shift towards increasing trends, evident from the 1980s onwards. The derived trend is strongest for St22006 in the southwest, where trends remain significant until the end of the record. St35005 also shows strong increasing trends for tests ending after 1980: however, these do not become significant until 1986.

For all stations, with the exception of St10002, a decreasing trend in annual mean flows is evident for analyses beginning after 1980. St10002 is largely an upland catchment draining the Wicklow Mountains and may be subjected to a different rainfall regime. The significant increasing trends for long-term annual flow for St25044 are lost for records ending after 2000. Overall, these results confirm those presented in Section 3. The consistency of results between the reconstructed and observed series increases confidence in the quality of flow reconstructions. These reconstructions also increase the utility of these series where investments in hydrometric measurements have been made over a number of decades. For ease of presentation seasonal results are only presented for St22006, which marks an interesting contrast to the eastern St7012 presented above.

From Fig. 5.8 positive trends are found only for tests beginning before the 1970s. In winter, increasing trends are evident for analyses ending after 1980. These trends are significant at the 5 percent level. For most other periods weak, non-significant increasing trends are evident. For shorter record lengths, beginning after 1980, trends tend to show weak decreases, but these are not reflective of longer records. The largest trends are found for spring mean flows where robust, persistent significant trends are found for records that commence before the 1960s.

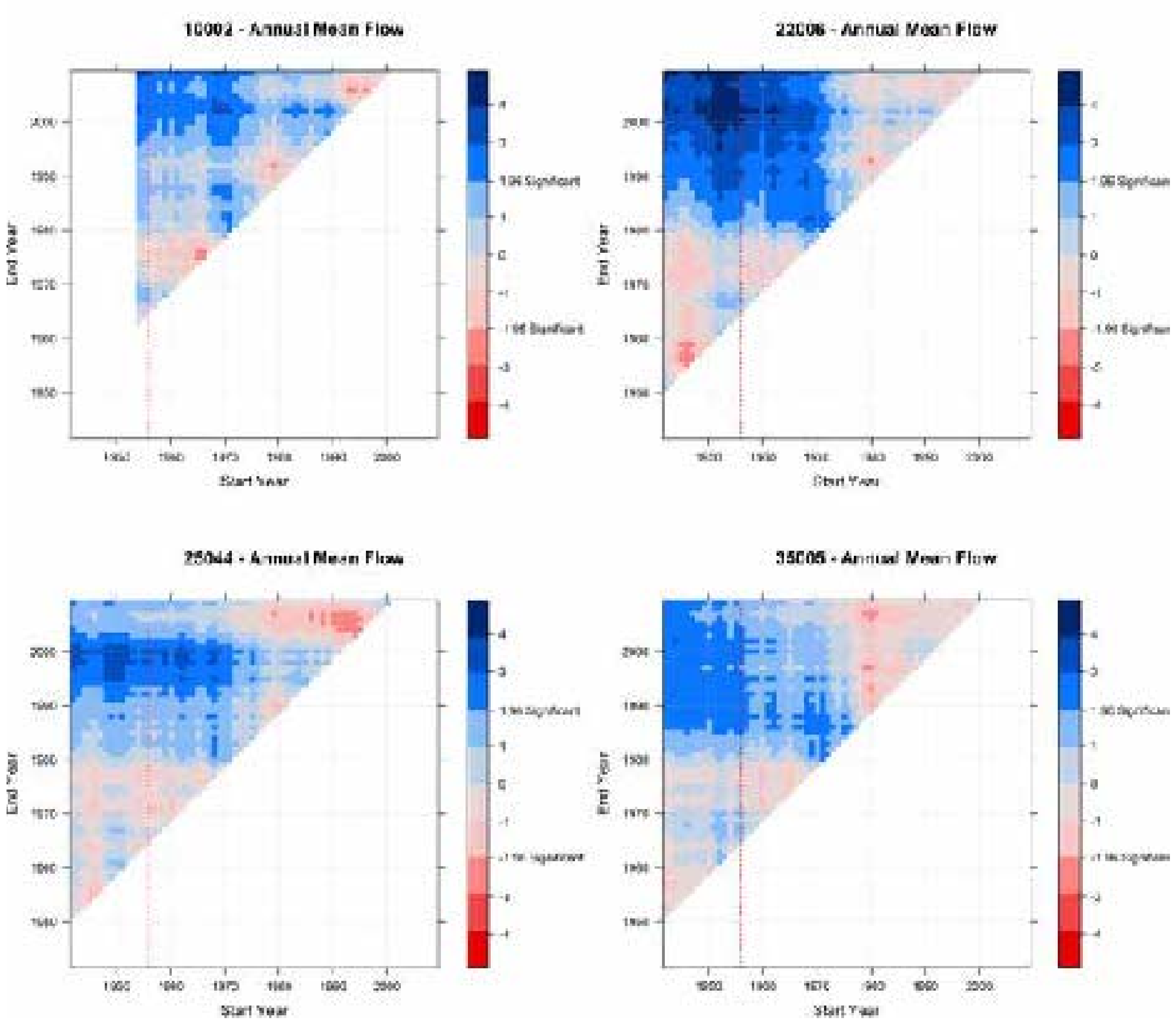

Figure 5.7. Moving windows analysis for reconstructed annual mean flows for four stations. The plots show the Mann-Kendall Zs statistic for all possible combinations of start and end dates (minimum record length of ten years). Red (blue) signifies decreasing (increasing) trends. Significance is tested at 5 percent level with |MK Zs| > 1.96. Trend shown to the left of the dashed vertical line represent extended duration series.

For this station these trends have become particularly strong with a Mann-Kendall Zs statistic of over three in recent decades. For shorter records these strong trends are not apparent with series beginning after the mid-1970s showing weak increasing or decreasing trends. In summer decreasing trends are evident from the beginning of the record up to the 1980s, after which trends become weakly positive. For summer, records with start years before 1970 show increasing trends that have emerged as significant since 2000. Similar results to summer are apparent for autumn mean flows.

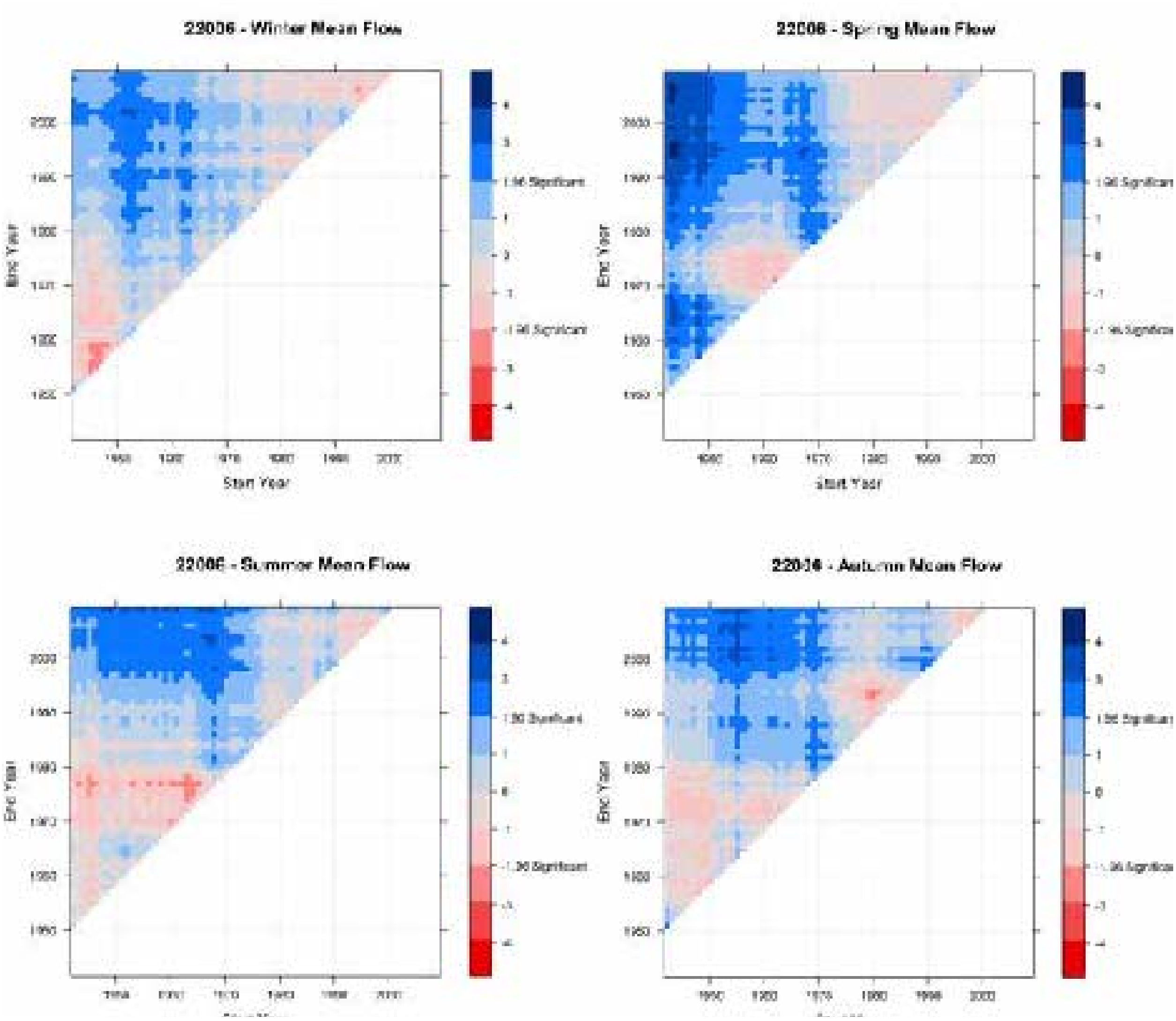

Figure 5.8. Moving windows analysis for reconstructed seasonal mean flows for the Flesk at Flesk Bridge. The plots show the Mann-Kendall Zs statistic for all possible combinations of start and end dates (minimum record length of 10 years). Red (blue) signifies decreasing (increasing) trends. Significance is tested at 5 percent level with |MK Zs| > 1.96.

5.4 Conclusions

This section presented reconstructed annual and seasonal mean flows for selected stations. These stations were identified as containing valuable information, despite shortcomings of drainage and missing data. Rainfall runoff models were used to reconstruct the flow series using observations of precipitation and evaporation. The trend analysis results derived from the reconstructed flows give confidence in thier usefulness. Three main contributions are made from the work on reconstructing river flows:

- In presenting the IRN in Section 2 it was noted that the eastern region was poorly represented. The reconstruction of flows for the Boyne at Slane Castle (St07012) and the Avonmore at Rathdrum (St10002) allow information on the evolution of trends to be derived from long record stations (particularly the Boyne), that would have been lost to the trend analysis based on even a large relaxation on the station-selection criteria used.

- The extension of river flow records adds valuable information for interpreting trends and contextualising shorter-term records. Particularly evident was the change in direction of trends in the 1980s towards increasing trends in annual and spring mean flows for the stations in the southwest and west. This change was not as marked for the eastern stations for records beginning before the 1970s.
- Results for the Boyne catchment in particular mean that the longest, continuous, and best-quality station in the country can be used in the analysis, with over forty years of data rescued. The results for this catchment highlight the importance of metadata in informing the interpretation of trend results and the difficulty associated with attributing change when confounding factors are present.

Overall, the reconstructed series revealed very similar results to the main analysis in Section 3, in particular the lack of trends in shorter records for winter, a lack of significant trends in summer and the large variability of spring mean flows. The results also highlighted the variability of trends throughout the record. For summer mean flows the influence of the mid-1970s' drought and the wet end of record became more apparent in the extended records and have a heavily confounding influence on summer trends. The largest trends in longer records were found for spring mean flows which showed significant increases for all long records.

6 Conclusions and Recommendations

6.1 The Irish Reference Network

This research established 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) were selected as part of the IRN. 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, complemented 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.

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 this area has been ongoing since the early 2000s in the UK and elsewhere. In furthering the utility and development of the network, a number of recommendations and areas for future work can be distilled:

- 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.
- Missing data can be problematic for the analysis of trends. With an average of 4.7 percent of missing data in IRN stations, efforts should be made to reduce the amount of missing data in future monitoring. In addition, future work should identify a formal approach for infilling missing data that is recognised and adopted by hydrometric agencies in Ireland.
- The quality of reference networks is founded on the availability and quality of metadata. While good metadata is available on the quality of measurements, different ranking categories are used by different hydrometric agencies. This makes it difficult to directly compare quality ratings. In addition, information on abstractions and discharges, and information on river engineering such as arterial-drainage programmes needs to be made more readily available to data users.
- In order to maximise the utility of the reference network, particularly for furthering our understanding of how changes in hydro-climatic processes are unfolding, the establishment of homogenised long-term rainfall series for each catchment in the network is recommended. Such homogenised series would also be particularly useful for modelling climate change impacts and land-use change.
- Within the IRN, there is a significant gap in spatial coverage in the west and east of the country. For climate change purposes, priority should be given to monitoring in these regions and when records mature the density of stations in these regions should be increased. A number of sites in the east of the country may meet the criteria for inclusion in the next iteration of the IRN. For the intervening

period, the reconstruction of river flows offers a viable avenue to supplementing the observed knowledge on climate variability and change in hydrological records.

- Long records of observations are vital for contextualising trends from shorter series. In the IRN there are a number of long records, but 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.

6.2 Climate-driven Trends from the Irish Reference Network

An in-depth analysis of trends in 22 river flow indicators describing the full range of flows was conducted for stations in the IRN, with the spatial distribution of trends across the network examined for the period 1976–2009. To shed light on the temporal development of trends their persistence for varying start dates and the variability of trends for all possible start and end dates were examined. The following key findings emerge:

- Trends in mean flows are highly complex and subject to large inter-annual and inter-decadal variability. For annual mean flows shorter records show non-significant decreases, however longer records show a tendency for statistically significant increasing trends (5 percent significance level). For winter mean flows decreasing trends are found for all stations outside of the west and northwest for the period 1976–2009. Strong decreases are found in the south and northeast of the country. The trends obtained from shorter records are not consistent with climate change scenarios of wetter winters, which are reflective of record length for most stations in the IRN. However, there is a tendency for non-significant increases in winter mean flow for longer record stations.
- Spring mean flows are dominated by natural variability. The record shows an increase in spring mean flows from the mid-1970s, consistent with the change point identified by Kiely (1999), which persists up to the mid-1990s, after which there is a considerable reduction in flows relative to this. This is evidenced in the trends derived with long records showing strong increasing trends in spring mean flows: however, shorter records show a large transition towards decreasing trends, especially in the south and southeast.
- Summer mean flows are dominated by increasing trends, some of which are statistically significant. Extremes at the start (mid-1970s drought) and end (recent wet summers) have had a large influence on trends. However, even when end of record extremes are removed increasing trends still dominate, while even the longest records show a dearth of persistent decreasing trends. Autumn mean flows are also dominated by increasing trends throughout the record, which are largest in the southeast.
- Annual and winter high flows are dominated by increasing trends; however, for the longest records significant trends have only emerged for tests ending after *c.* 2000. Shorter records show considerably fewer significant trends. Summer high flows are dominated by increasing trends and spring high flows show the same transition from increasing to decreasing trends as spring mean flows.
- Low flows are heavily influenced by the drought of the 1970s, the historical legacy of network expansion at this point in time and exceptionally wet years at the end of record, making it difficult to extract robust trends. For the period 1976–2009 no decreasing trends in the minimum 7-day flow are found throughout the network (with the exception of one NI station). Longer records show no clear direction or patterns in trends. The greatest prevalence for decreasing trends are found for winter low flows (W_Q90), which show some significant decreasing trends for records beginning in the mid-1960s onwards. It appears that it is this trend that is important in driving decreases in winter mean flows for shorter 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 regional-scale driver.

Trends in Irish river flows are strongly correlated with the winter NAO. As highlighted in previous research (Kiely, 1999) changes in the NAO have been linked with changes in Irish hydro-climatic variables. A shift towards more negative winter NAO 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 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, rather than solely the NAO.

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. This should not be surprising given the large variability of river flows relative to potential climate change signals. 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.

6.3 Detectability of Climate Change Signals

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 river flow 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. The analysis of observations confirms this, with few statistically significant trends identified to date. High flows, on the other hand, show greater potential for early detection of climate change signals.

For detecting climate change it may be prudent that a distinction is made between practical and statistical significance. Even where trends have not been detected 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 *et al*., 2012). 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 of anthropogenic climate change is substantial 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. Reference networks facilitate tracking the emergence of climate change signals relative to natural variability and provide information, free from confounding factors, for validating output from climate change impact assessments and the development of adaptation policies.

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Acronyms and Annotations

ACF	Autocorrelation function
BS	Boot strapping
CEH	Centre for Ecology and Hydrology
CRR	Conceptual Rainfall Runoff Model
CV	Coefficient of variation
EPA	Environmental Protection Agency
FSU	Flood Studies Update
GCOS	Global Climate Observing System
HCDN	Hydro-Climatic Data Network
ICARUS	Irish Climate Analysis and Research UnitS
ICSU	International Council for Science
IOC	Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO)
IPCC	Intergovernmental Panel on Climate Change
IRN	Irish Reference Network
JD	Julian Day
L	Block length
LAs	Local authorities
Loess	Local Polynomial Regression Fitting
MK	Mann-Kendall
n	number of samples
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
NI	Northern Ireland
NRFA	National River Flow Archive
NSE	Nash Sutcliffe Efficiency
OPW	Office of Public Works
r	Serial correlation
RBD	River Basin District
RHBN	Reference Hydrometric Basin Network
RHNs	Reference Hydrometric Networks
SE	Seasonality indicator
STRIVE	Science, Technology, Research and Innovation for the Environment

TSA	Theil-Sen Approach
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
WCRP	World Climate Research Programme
WFD	Water Framework Directive
WMO	World Meteorological Organization
Zs	Z statistic

Appendix 1 Details of Hydrometric Stations selected as part of the Irish Reference Network

FSU Rating: Quality of flood rating category given by Irish Flood Studies Update (A1 best to Unusable). ***Area Km²***: Catchment area from 2012 register of hydrometric gauges (EPA, 2012). ***Start Record***: Start year of available online digitised time series data. ***Start Analysis***: Appropriate start year for analysis of data under study criteria. ***Length (Yrs):*** Length of analysis period – from start analysis to 2009 end year. ***% missing***: Percentage of data missing within the time series. ***Infilled***: Identifies if missing data has been infilled. ***%Q95***: Percentage impact of abstractions on the natural flow at, or in excess of the Q95 exceedance threshold value. ***FARL***: Flood Attenuation by Reservoirs and Lakes Flood Studies Update descriptor. ***Drained***: Identifies if the catchment has been subject to arterial drainage and the years in which works were undertaken.

Station	Information	Value	Information	Value	FSU Station Remark	Indicators analysed/ notes
06013 – OPW (NB)	FSU rating	A1	Infilled	Y	Velocity-area station installed and automated in 1975. Fairly uniform channel with smooth concrete bed upstream of Flat V crump weir acting as a control.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	309.1	% missing	0.96		
Charleville Weir	Start record	1975	% of Q95	NA		
	Start analysis	1976	FARL	0.971		
	Length (Yrs)	34	Drained: N			
06014 – OPW (NB)	FSU rating	A1	Infilled	Y	Velocity-area station installed and automated in 1975. Fairly uniform channel with smooth concrete bed upstream of Flat V crump weir acting as a control.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	270.4	% missing	2.35		
Tallanstown Weir	Start record	1975	% of Q95	2.44		
	Start analysis	1976	FARL	0.971		
	Length (Yrs)	34	Drained: 50-57 (FSU)			
07009 – OPW (E)	FSU rating	A1	Infilled	Y	Automated velocity-area station installed in 1939, automated in 1954. New crump weir installed 28/10/76 (A1 rating post 76 only). Prior to this site had a natural channel with a stable gravel bed.	Core and Low indicators analysed. High flows (MAX10) and IAMAX not analysed.
	Area (Km²)	1683.8	% missing	1.76		
Navan Weir	Start record	1976	% of Q95	4.86		
	Start analysis	1977	FARL	0.986		
	Length (Yrs)	33	Drained: N			
07012 – OPW (E)	FSU rating	A1	Infilled	Y	Velocity-area station installed and automated in 1940. Gravel bed. Weed growth all year round. Weir acts as a control. Straight approach conditions.	Core, High, Low and IAMAX indicators analysed. Post 1981 used due to large extent of drainage. Too short for fixed period analysis.
	Area (Km²)	2460.3	% missing	0.39		
Slane Castle	Start record	1940	% of Q95	NA		
	Start analysis	1982	FARL	0.965		
	Length (Yrs)	28	Drain:69-86 (OPW)			
12001 – OPW (SE)	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in and 1955. Natural channel with a stable gravel bed. Natural channel control.	Core, High and IAMAX indicators analysed. Low flows (MIN7) not analysed.
	Area (Km²)	1030.8	% missing	2.28		
Scarawalsh	Start record	1955	% of Q95	NA		
	Start analysis	1956	FARL	0.99		
	Length (Yrs)	54	Drain:N			
14007 – OPW (SE)	FSU rating	A1	Infilled	Y	Automated velocity-area station installed in 1940, automated in 1980. Stable gravel bed. Natural channel control.	Core, High, Low and IAMAX indicators analysed. Too short for fixed period analysis.
	Area (Km²)	94.9	% missing	1.99		
Derrybrock	Start record	1980	% of Q95	NA		
	Start analysis	1981	FARL	1		
	Length (Yrs)	29	Drain:N			

Station	Information	Value	Information	Value	FSU Station Remark	Indicators analysed/ notes
14019 – OPW (SE) Levitstown	FSU rating	A1	Infilled	Y	Velocity-area station installed 1941 and automated 1953. Stable mud channel. Seasonal weed growth. Natural channel control. Slight scatter a high flows and hard to define top end. Cannot extrapolate beyond 3.91m (HGF).	Core, High and IAMAX indicators analysed. Low flows (MIN7) not analysed.
	Area (Km²)	1697.3	% missing	6.51		
	Start record	1955	% of Q95	1.06		
	Start analysis	1955	FARL	1		
	Length (Yrs)	55	Drain: N			
15001 – OPW (SE) Annamult	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in 1939, automated in 1954. Stable mud bed. Natural channel control. Some backwatering known to happen from the R. Nore.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	444.3	% missing	1.77		
	Start record	1972	% of Q95	NA		
	Start analysis	1973	FARL	1		
	Length (Yrs)	37	Drain: N			
15003 – OPW (SE) Dinin Bridge	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in 1953. Natural section. Gaugings scattered at lower end of rating.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	299.2	% missing	2.86		
	Start record	1972	% of Q95	28.94		
	Start analysis	1973	FARL	0.997		
	Length (Yrs)	37	Drain: N			
15006 – OPW (SE) Brownsbarn	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in 1939, automated in 1953. Stable rock bed and natural channel control.	Core, High, Low and IAMAX indicators analysed. Poor quality low-flow data up to 01/10/74 - to be used for indicative purposes only (OPW).
	Area (Km²)	2418.3	% missing	0.55		
	Start record	1972	% of Q95	NA		
	Start analysis	1973	FARL	0.99		
	Length (Yrs)	37	Drain: N			
16008 – OPW (SE) New Bridge	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in 1940, automated in 1954. Stable stone bed. Natural channel control.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	1090.3	% missing	3.67		
	Start record	1954	% of Q95	NA		
	Start analysis	1955	FARL	0.99		
	Length (Yrs)	55	Drain: N			
16009 – OPW (SE) Caher Park	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in 1940, automated in 1953. Stable stone bed and natural channel control. Seasonal weed growth effects bottom of ratings.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	1582.7	% missing	0.59		
	Start record	1953	% of Q95	NA		
	Start analysis	1954	FARL	0.998		
	Length (Yrs)	56	Drain: N			
18002 – OPW (SW) Ballyduff	FSU rating	B	Infilled	Y	Velocity-area station installed in 1940, automated in 1955. Bridge location. Natural channel control. Stable stone bed.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	2333.7	% missing	0.61		
	Start record	1955	% of Q95	NA		
	Start analysis	1956	FARL	0.99		
	Length (Yrs)	54	Drain: N			
18003 – OPW (SW) Killavullen	FSU rating	A2	Infilled	Y	Velocity area station installed in 1940 and automated in 1951. Stable gravel bed, minimal weed growth, 3 arched bridge. Natural channel control.	Core, High, Low and IAMAX indicators analysed. Change in reliability limit pre and post 1971. Post 1973 used.
	Area (Km²)	1256.7	% missing	3.07		
	Start record	1955	% of Q95	1.5		
	Start analysis	1973	FARL	0.99		
	Length (Yrs)	37	Drain: N			

Station	Information	Value	Information	Value	FSU Station Remark	Indicators analysed/ notes
18005 – OPW (SW) Downing Bridge	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	A2 378.5 1972 1973 37	Infilled % missing % of Q95 FARL Drain: N	N 0.28 NA 1	Automated velocity-area station installed in 1955. Natural channel, bridge acts as a control. Debris does accumulate on bridge buttresses, but regularly cleared.	Core, High, Low and IAMAX indicators analysed. Debris caught on D/S face of bridge, almost totally blocked - Levels raised artificially high (OPW – 17-10-1997).
18006 – EPA (SW) Cset mallow	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	B 1054.8 1977 1978 32	Infilled % missing % of Q95 FARL Drain: N	Y 5.09 1.12 0.99	Some concerns over a very high gauging taken upstream. Need for more high-flow gaugings. No site description available from FSU.	Core, Low and High indicators analysed. IAMAX not analysed.
18050 – EPA (SW) Duarrigle	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	B 248.8 1981 1982 28	Infilled % missing % of Q95 FARL Drain: N	Y 3.6 NA 0.99	No site description available from FSU.	Core, Low and High indicators analysed. IAMAX not analysed.
19001 – OPW (SW) Ballea	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	A2 103.3 1972 1973 37	Infilled % missing % of Q95 FARL Drain: N	Y 3.76 NA 1	Automated velocity-area station installed in 1956. Open channel prior to 1974. Flat V weir installed 26/11/74.	Core and Low indicators analysed. High flows (MAX10) and IAMAX not analysed.
21002 – EPA (SW) Coomhola	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	Un 64.8 1975 1976 34	Infilled % missing % of Q95 FARL Drain: N	Y 4.18 0.14 NA	No site description available from FSU.	Core, Low and High indicators analysed. IAMAX not analysed.
23002 – OPW (SH) Listowel	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	A1 646.8 1946 1961 49	Infilled % missing % of Q95 FARL Drain: 51-59 (OPW)	Y 5.46 NA 1	Automated velocity-area station installed in 1940 and automated in 1946. Unstable gravel bed and natural channel with bridge as partial control, acting like a flume. Site was moved upstream 200m (18-11-1974).	Core, Low and IAMAX indicators analysed. High flows (MAX10) not analysed.
25001 – OPW (SH) Annacotty	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	A2 647.6 1972 1974 36	Infilled % missing % of Q95 FARL Drain: 20s-30s (FSU)	Y 9.09 NA 0.99	Velocity area station installed in 1940 and automated in 1953. Gravel bed. Excavation for flood relief scheme in 1997 and 1999 doesn't appear to have any significant effect on stage discharge relationship.	Core, Low and High indicators analysed. IAMAX not analysed.
25002 – OPW (SH) Barrington's Bridge	FSU rating Area (Km^2) Start record Start analysis Length (Yrs)	A2 221.6 1953 1954 56	Infilled % missing % of Q95 FARL Drain: 20s-30s (FSU)	Y 3.43 NA 0.99	Velocity area station installed in 1940 and automated in 1953. Smooth concrete bed, negligible weed growth. Non-standard weir acts as a control.	Core, Low and High indicators analysed. IAMAX not analysed. Construction works on weir 1997-1998 (OPW). Future work should re-assess station inclusion in the IRN.

Station	Information	Value	Information	Value	FSU Station Remark	Indicators analysed/ notes
25006 – OPW (SH)	FSU rating	A1	Infilled	Y	Velocity-area station installed in 1940 and automated in 1947. Drainage 48-55. Stable sand/silt bed. Natural channel control.	High and IAMAX indicators analysed. Core and Low flows (MIN7) not analysed as water levels affected by hydro generation downstream (EPA comment).
	Area (Km²)	1162.8	% missing	6.81		
Ferbane	Start record	1952	% of Q95	NA		
	Start analysis	1956	FARL	0.955		
	Length (Yrs)	54	Drain: 48-55 (OPW)			
25030 – OPW (SH)	FSU rating	A1	Infilled	Y	Velocity-area station installed in 1940 and automated in 1957. Natural channel control. Stable bed consisting of boulders.	Core and Low indicators analysed. High flows (MAX10) and IAMAX not analysed.
	Area (Km²)	280	% missing	3.95		
Scarriff	Start record	1972	% of Q95	NA		
	Start analysis	1973	FARL	0.85		
	Length (Yrs)	37	Drain: N			
26009 – OPW (SH)	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in 1939 and automated in 1957. Unstable gravel bed. Natural channel control. Seasonal weed effects at lower end of rating.	Core, High and IAMAX indicators analysed. Low flows (MIN7) not analysed as low-flow ratings truncated (OPW).
	Area (Km²)	90.5	% missing	8.59		
Bellantra Bridge	Start record	1972	% of Q95	NA		
	Start analysis	1973	FARL	0.936		
	Length (Yrs)	37	Drain:N			
26021 – OPW (SH)	FSU rating	A2	Infilled	Y	Velocity-area station installed in 1939 and automated in 1965. Open channel with natural control.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	1098.8	% missing	6.53		
Ballymahon	Start record	1972	% of Q95	NA		
	Start analysis	1976	FARL	0.807		
	Length (Yrs)	34	Drain:60-68 (OPW)			
26029 – EPA (SH)	FSU rating	C	Infilled	N	No site description available from FSU.	Core and Low indicators analysed. High flows (MAX10) and IAMAX not analysed.
	Area (Km²)	116.9	% missing	3.32		
Dowra	Start record	1975	% of Q95	0.21		
	Start analysis	1976	FARL	NA		
	Length (Yrs)	34	Drain: N			
27002 – OPW (SH)	FSU rating	A1	Infilled	N	Velocity-area station installed in 1940 and automated in 1954. Flat V crump weir acts as control. Stable bed, negligible weed growth.	Core, High, Low and IAMAX indicators analysed.
	Area (Km²)	511.4	% missing	1.55		
Ballycorey	Start record	1956	% of Q95	1.52		
	Start analysis	1955	FARL	0.835		
	Length (Yrs)	55	Drain: N			
32012 – EPA (W)	FSU rating	A2	Infilled	Y	No site description available from FSU.	Core, Low and High indicators analysed. IAMAX not analysed.
	Area (Km²)	146.2	% missing	9.19		
Newport weir	Start record	1981	% of Q95	NA		
	Start analysis	1982	FARL	0.843		
	Length (Yrs)	28	Drain: N			
34001 – OPW (W)	FSU rating	A2	Infilled	Y	Automated velocity-area station installed in 1939 and automated in 1968. Stable gravel bed. Natural channel control.	Core indicators analysed. High (MAX10), low (MIN7) and IAMAX flows not analysed as high and low ratings truncated (OPW).
	Area (Km²)	1974.8	% missing	4.44		
Rahans	Start record	1974	% of Q95	NA		
	Start analysis	1975	FARL	0.825		
	Length (Yrs)	35	Drain: 60-71 (OPW)			
35002 – OPW (W)	FSU rating	A2	Infilled	Y	Velocity area station installed in 1939 and automated in 1955.	Core, Low and High indicators analysed. IAMAX not analysed.
	Area (Km²)	81.1	% missing	12.51		
Billa bridge	Start record	1972	% of Q95	NA		
	Start analysis	1973	FARL	0.986		
	Length (Yrs)	37	Drain: N			

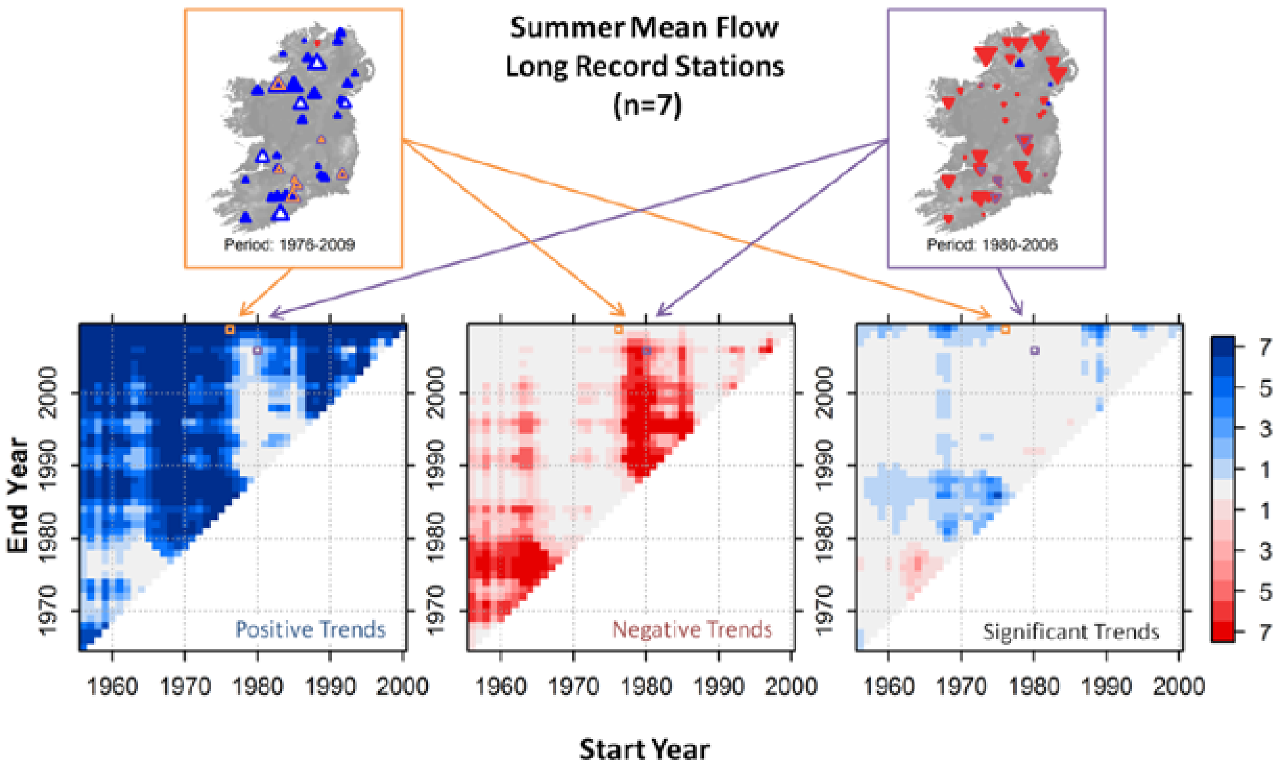
Station	Information	Value	Information	Value	FSU Station Remark	Indicators analysed/ notes
35005 – OPW (W) Ballysadare	FSU rating Area (Km²) Start record Start analysis Length (Yrs)	A2 639.7 1946 1947 63	Infilled % missing % of Q95 FARL Drain:N	Y 15.27 NA 0.898	Automated velocity-area station installed and automated in 1945. Stable gravel bed. Natural channel with bridge as partial control.	Core, High and IAMAX indicators analysed. Low flows (MIN7) not analysed.
36010 – OPW (NW) Butlers Bridge	FSU rating Area (Km²) Start record Start analysis Length (Yrs)	A1 771.7 1972 1972 38	Infilled % missing % of Q95 FARL Drain:N	Y 12.68 5.25 0.86	Automated velocity-area station installed in 1941 and automated in 1955. Stable rock bed. Natural channel control.	Core, High and IAMAX indicators analysed. Low flows (MIN7) not analysed. Poor low-flow rating, weed growth (EPA comment).
38001 – OPW (NW) Clonconwal Ford	FSU rating Area (Km²) Start record Start analysis Length (Yrs)	B 111.2 1972 1973 37	Infilled % missing % of Q95 FARL Drain:N	Y 12.23 NA 0.922	Velocity area station installed in 1939 and automated in 1957.	Core, Low and IAMAX indicators analysed. High flows (MAX10) not analysed.
39006 – EPA (NW) Claragh	FSU rating Area (Km²) Start record Start analysis Length (Yrs)	NonFSU 245.1 1977 1978 32	Infilled % missing % of Q95 FARL Drain: N	Y 3.7 NA NA	Not a FSU station.	Core, Low and High indicators analysed. IAMAX not analysed.

Appendix 2 Interpretation of Moving Windows Plots

The moving window plots allow the assessment of the direction and significance of trends for all combinations of start and end dates and therefore allow a full exploration of the evolution of climate-driven changes. In Section 3 we use this approach for long record stations (marked by highlighted triangles on the maps below). Examples of how two fixed periods with different start and end dates are included in the plots are shown. The added detail from the traditional fixed-period analysis is apparent where a single fixed period plots as a single cell.

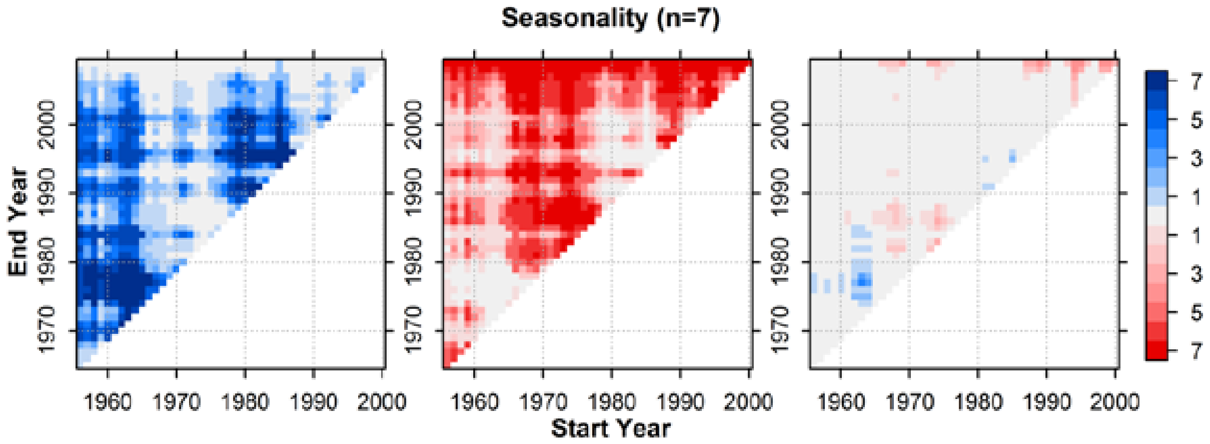
The plots count the number of stations showing the same direction of trend and the number of stations showing the dominant statistically significant trends using colour ramps. Periods within the time series for which increasing trends are found are shown in blue on the left. Periods within the time series for which decreasing trends are found are shown in red in the centre. Finally, periods within the time series where increasing or decreasing trends are found to be significant at the 0.05 level using the Mann-Kendall test (|Zs|>1.96) are plotted on the right where blue represents a dominant significant increasing trend and red a dominant significant decreasing trend.

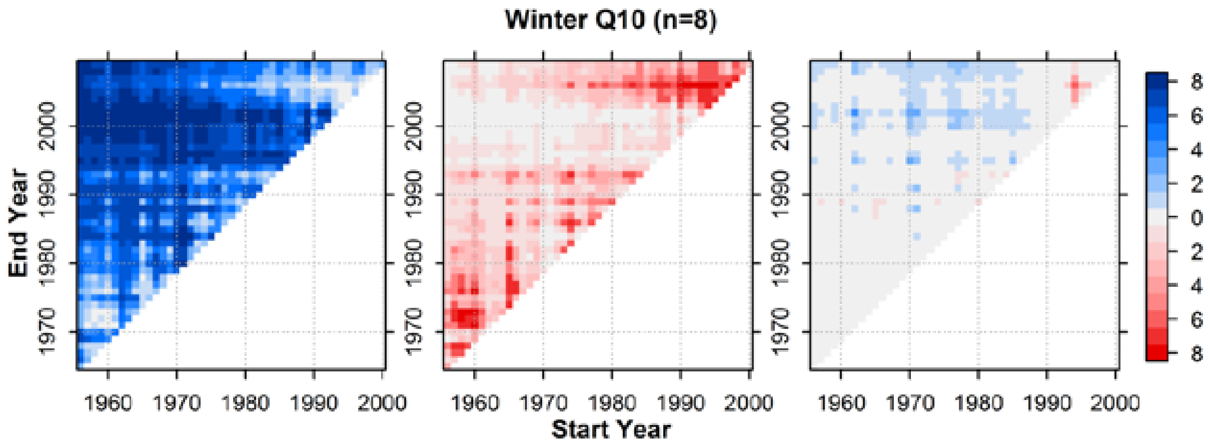
Clear patterns of change can be seen from these plots including key periods in the series where trends change direction or become significant. For example, the influence of the wet end year of 2009 can be seen with all stations showing increasing trends independent of start year, many of which are statistically significant. The influence of specific start years can also be seen: for example, trend tests starting around 1970 show increasing trends across the majority of the stations. The ability to rapidly assess the evolution of trends in this way is a major addition to the traditional fixed period analysis.

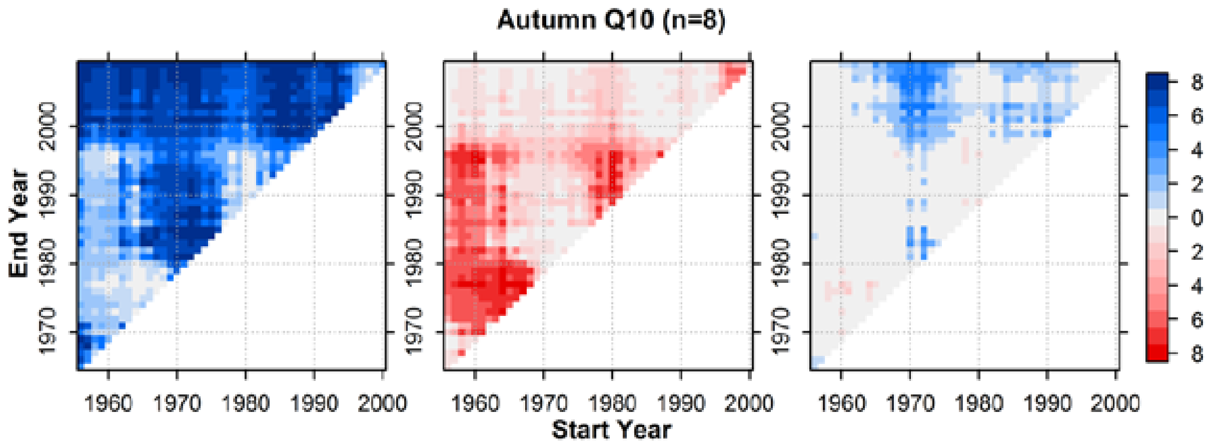


Appendix 3 Moving Windows Analysis for Remaining Indicators

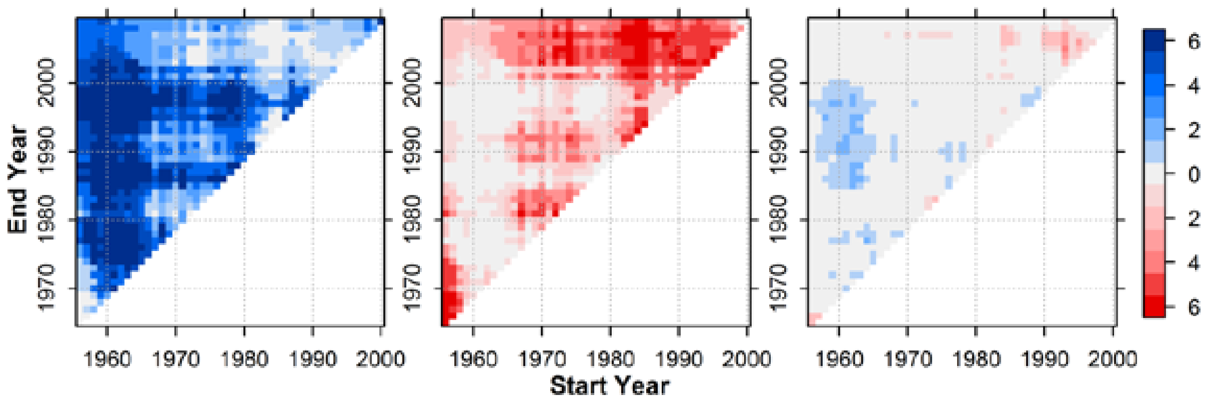
Moving windows analysis of trends for all possible start and end dates for indicators not included in Section 3. Left-hand panel shows increasing trends, centre panel shows decreasing trends and right-hand panel shows increasing and decreasing trends found to be significant at the 5 percent level. n indicates the total number of stations analyzed.



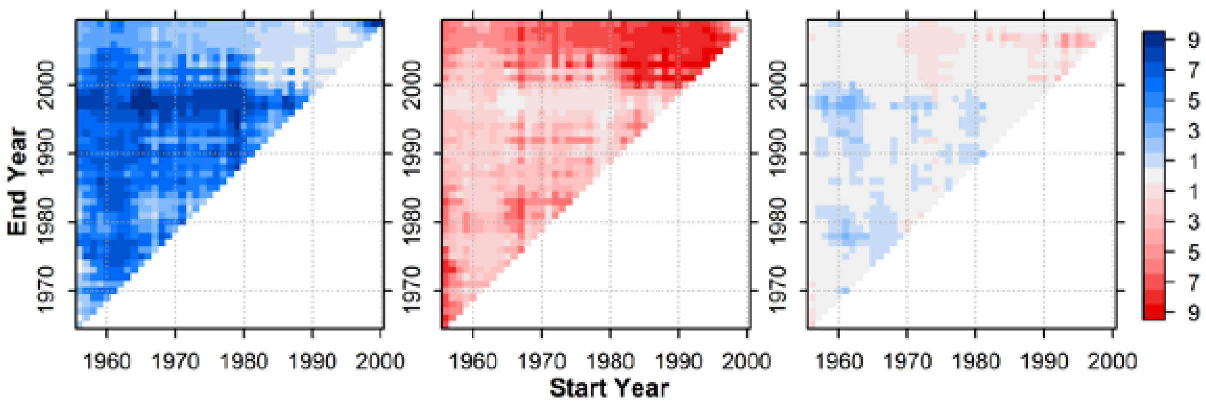




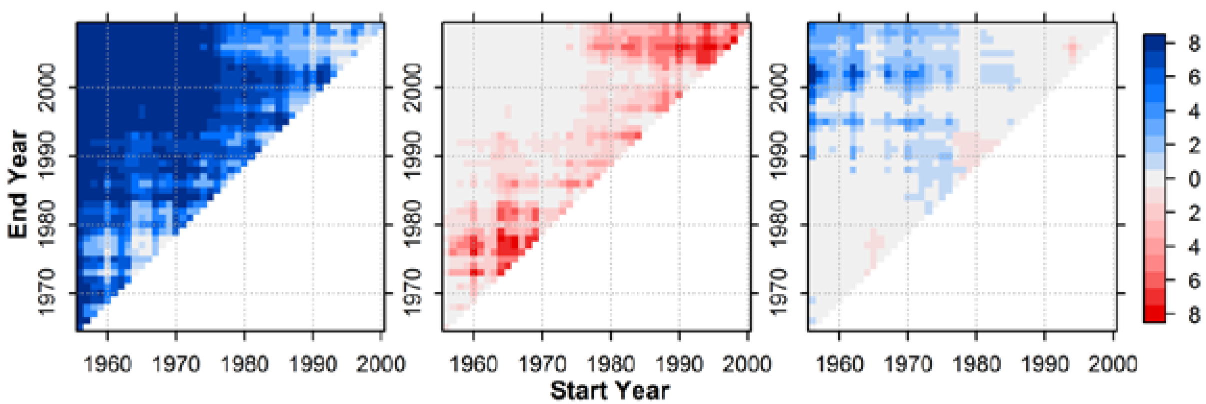
IAMAX JD (n=6)



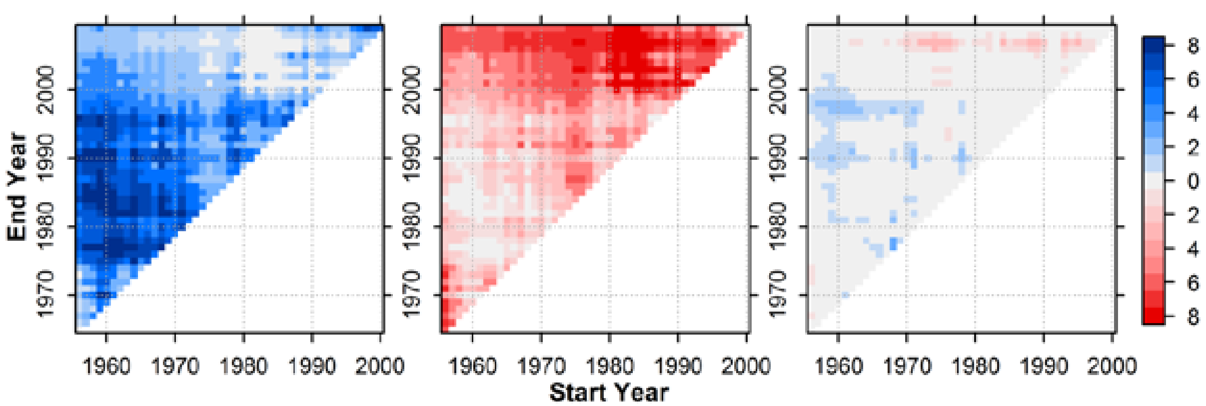
MAX10 JD (n=9)

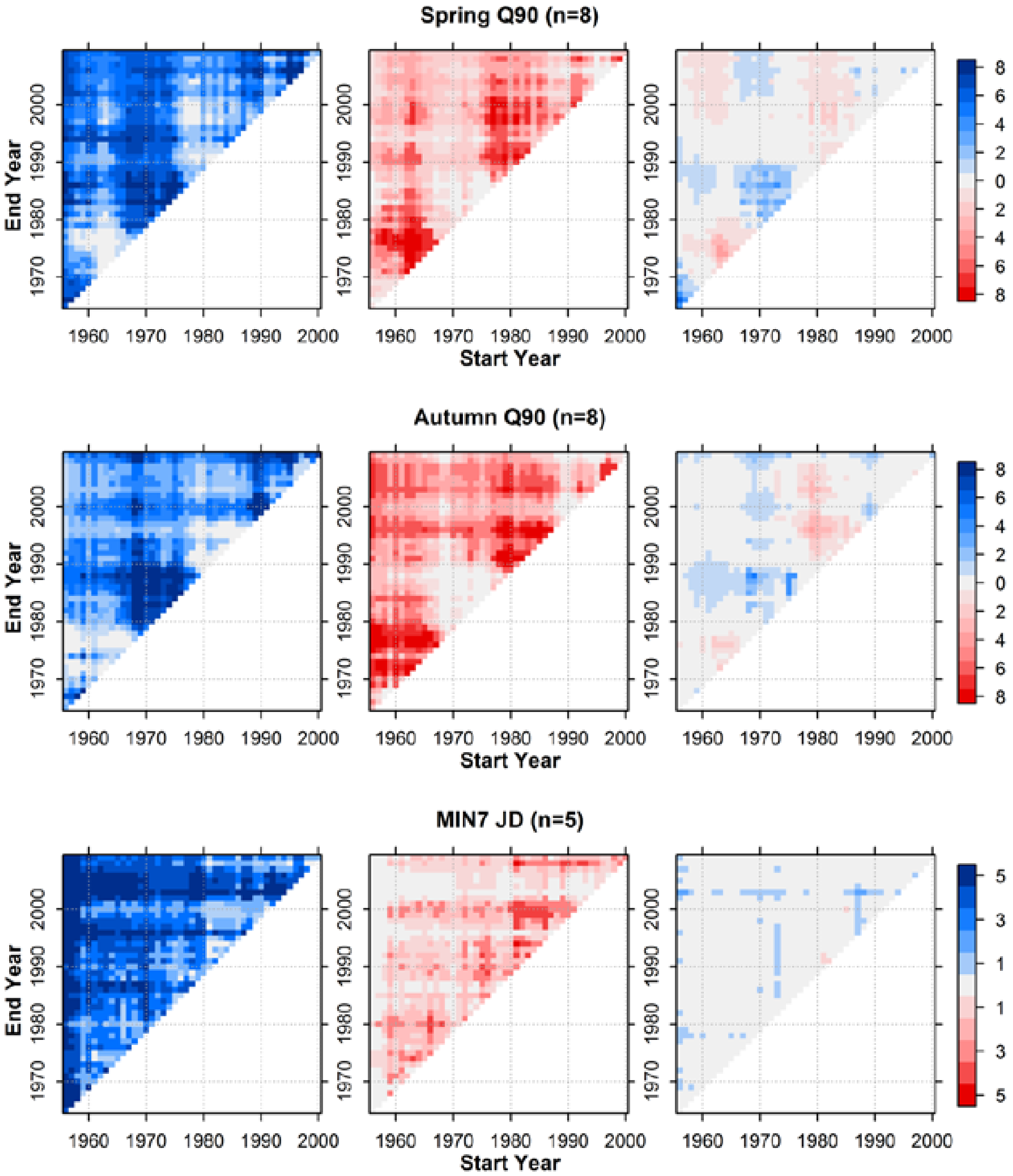


MAX30 (n=8)



MAX30 JD (n=8)




Spring Q90 (n=8)
End Year
Start Year
Autumn Q90 (n=8)
End Year
Start Year
MIN7 JD (n=5)
End Year
Start Year
1960
1970
1980
1990
2000
8
6
4
2
0
2
4
6
8
5
3
1
1
3
5

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil, Pobal agus Rialtais Áitiúil.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail;
- scardadh dramhuisce;
- dumpáil mara.

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

Climate Change Research Programme (CCRP) 2007-2013

The EPA has taken a leading role in the development of the CCRP structure with the co-operation of key state agencies and government departments.
The programme is structured according to four linked thematic areas with a strong cross cutting emphasis.
Research being carried out ranges from fundamental process studies to the provision of high-level analysis of policy options.

For further information see
www.epa.ie/whatwedo/climate/climatechangeresearch

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