Development and analysis of a homogeneous long-term precipitation network (1850-2015) and assessment of historic droughts for the island of Ireland.

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Abstract

Long-term precipitation series are critical for understanding emerging changes to the hydrological cycle. Given the paucity of long-term quality assured precipitation records in Ireland this thesis expands the existing catalogue of long-term monthly precipitation records for the Island by recovering and digitising archived data. Following bridging and updating, 25 stations are quality assured and homogenised using state-of-the-art methods and scrutiny of station metadata. Assessment of variability and change in the homogenised and extended precipitation records for the period 1850-2010 reveals positive (winter) and negative (summer) trends. Trends in records covering the typical period of digitisation (1941 onwards) are not always representative of longer records. Using this quality assured network of precipitation stations together with proxy rainfall reconstructions a 250-year historic drought catalogue is established using the Standardised Precipitation Index (SPI). Documentary sources, particularly newspaper archives, spanning the last 250 years are used to (i) add confidence to the quantitative detection of drought episodes and (ii) gain insight to the socio-economic impacts of historic droughts. During the years 1850-2015 seven major drought rich periods with an island wide fingerprint are identified in 1854-1860, 1884-1896, 1904-1912, 1921-1924, 1932-1935, 1952-1954 and 1969-1977. These events exhibit substantial diversity in terms of drought development, severity and spatial occurrence. Results show that Ireland is drought prone but recent decades are unrepresentative of the longer-term drought climatology. Finally, long-term homogenous precipitation records are further utilised to reconstruct river flows at twelve study catchments to 1850. Reconstructed flows are analysed to identify periods of hydrological drought and the potential of different SPI accumulations to forecast severe drought are explored. Results demonstrate the importance of catchment characteristics in moderating the effects of meteorological drought and highlight the potential for drought forecasting in groundwater dominated catchments. The body of work presented considerably advances understanding of the long-term hydro-climatology of a sentinel location in Europe and provides datasets and tools for more resilient water management.

Acknowledgements

I would like to thank Met Éireann for allowing me access to the archived hard copy records. I would also like to say thank you to Mairead Treaner who is the librarian in Met Éireann for all her help with the records and advice over the past 4 years. I would like to acknowledge my colleagues John Coll for training in HOMER as well as Chris Brunsdon, Julia Hall and Shaun Harrigan for all their help with the R programming. I would like to say a special thank you to Prof. Jan Rigby who gave me great advice and supported me so much during my PhD. I also acknowledge Maynooth University for initially awarding me the John and Pat Hume PhD scholarship and the Irish Research Council for funding me for the final two years of my PhD research. I thank my external examiner Dr Neil Macdonald and my internal examiner Prof. Peter Thorne for taking time to examine me on my thesis and for their fair, supportive and constructive comments. I would like to say thank you to all my friends and colleagues in ICARUS who have given me great encouragement, support and a good laugh over the past 4 years. I thank my supervisor Dr Conor Murphy, for all his insightful advice and encouragement over the past 5 years. I would not have achieved my PhD without Conor’s guidance and I now consider him to be a good friend. I thank my Mum and Dad for always being interested in my work even if they did not understand what I was doing at times. Finally, I thank my beautiful and patient wife Maggie and my three gorgeous daughters Izzy, Hannah and Keri for all their love, understanding and support during my academic journey, I owe them so much!

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1 Introduction

1.1 Background and rationale

The Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (2014) states that it is "extremely likely" that human induced increases in greenhouse gases concentrations and other anthropogenic forcings have contributed over half the observed increases in global temperature from 1951-2010 (IPCC, 2014). Observed changes in temperature have resulted in increased atmospheric moisture, causing changes in the global hydrological cycle and precipitation patterns (Bates *et al.,* 2008; Allan, 2011; Wu *et al.,* 2013 Watts *et al.,* 2015). These changes to the hydrological cycle have affected the quantity and quality of water resources across many regions (Huntington, 2006; Barnett *et al.*, 2008; Bates *et al.,* 2008; Allan, 2011; IPCC, 2014). The past 30 years have seen changes in precipitation, with increased precipitation experienced in the northern hemisphere and decreases across some regions (IPCC, 2014).

Future projections suggest increases in the intensity and variability of precipitation across many areas, but these changes are not consistent, with increased risk from flooding across most areas and likely increases in summer drought in other regions (Bates *et al.,* 2008; IPCC, 2014). These expected changes in precipitation will increase the risk to populations living in urban areas from flooding, landslides, drought, water scarcity and sea level rise (IPCC, 2014). Populations living in rural areas are expected to experience reduced water availability, food security and agricultural production with changes in areas of food production "highly likely" (IPCC, 2014). However, uncertainty is a key issue with future climate projections due to uncertainty associated with future changes in temperature and particularly rainfall (Bates *et al.,* 2008; Hawkins and Sutton, 2009; Prudhomme *et al.,* 2014; Jenkins *et al.,* 2015). Uncertainties associated with future projections of rainfall and associated variables are large with signals unlikely to exceed variability by at least the first half of century (Hawkins and Sutton, 2011; IPCC, 2014).

Detecting change in observations can be a challenging task. Due to natural climate variability, trends that are identified in short records often do not reflect the long-term climatic changes (Wilby, 2006; IPCC, 2014; De Saedeleer, 2016). Hence, long-term good quality climate records together with supporting metadata are necessary to conduct robust climate analysis. Long records help climate scientists better understand, identify, predict and adapt to climate variability and change and also ground truth climate models (Barker *et al.,* 2004; Wilby *et al.,* 2006; Brunet *et al.,* 2013; Prohom *et al.,* 2015).

In realising the value of long records previous research has used long-term precipitation records to place recent changes and extreme hydrological events into a wider historical context (e.g. Jones *et al.,* 2006; Marsh *et al.*, 2007; Todd *et al.*, 2013; Burt *et al.,* 2014; Spraggs *et al.*, 2015; Watts *et al.,* 2015). The advantages of long-term records are that emerging trends, if any, can be identified more accurately, as well as providing useful information on how these records have changed and fluctuated over longer periods of time (Barker *et al.,* 2004; Wilby, 2006, Wilby *et al.,* 2015; Burt *et al.,* 2014; Todd *et al.,* 2014). Long records can also be used to inform society of potential impacts from variability and change (WMO, 2014).

In developing long records of key climate variables, many studies across Europe and the UK have integrated historical documentary and proxy evidence into hydro-climatology research to reconstruct past weather, climate, the frequency and severity of extreme events and to validate past observations (Brázdil *et al.,* 2006; Macdonald, 2006; Pfister *et al.,* 2006; Casty *et al.,* 2007; Pauling *et al.,* 2006; Macdonald, 2013; Kjeldsen, *et al.,* 2014; MacDonald *et at.,* 2014; Benito *et al.,*2015). All these studies note the importance and value of historical documentary and proxy evidence. The integration of documentary evidence into historical hydro-climatology research has the potential to greatly reduce some of the uncertainty associated in using historical observations (Macdonald *et al.,* 2014). There are many documentary and proxy sources available but some noteworthy sources of evidence on past climate include:

Newspaper and old journal articles which often contain information on past extreme weather events such as floods, drought and extreme heat as well as details on socio economic impacts (Brázdil *et al.,* 2005).

Census of population during the 19th Century census information often contained information regarding past weather extreme events. In addition, past Census can provide important and useful details of the socio-economic impacts of the time from such extremes (Census, 1851).

Early instrumental meteorological observations which were often started in places long before the national meteorological services in the 19th century (Brázdil *et al.,* 2005).
Early scientific papers, books and communications can also provide information on past weather extremes, occurrence, causes and impacts (Brázdil *et al.,* 2005).

Unlike the UK and Europe most research into historic changes in precipitation in Ireland has been conducted over relatively short records spanning the period of available digitised records, typically 1940 onwards (e.g. Kiely, 1999; Sheridan, 2001; Wang *et al.,* 2006; Leahy and Kiely, 2011; Dwyer, 2012). However, there are some long-term precipitation records available for Ireland which seems to have been neglected by most previous research. Tabony (1980) and Briffa (1984) compiled or constructed long-term historical monthly precipitation records using observations at 185 stations across Europe dating from 1861, or earlier. These long-term precipitation records for the UK and Ireland have been subsequently updated and analysed by studies in the UK (Jones, 1983; Gregory *et al.,* 1991 Jones and Conway, 1997; Burt *et al.,* 2014).

There are a limited number of studies that have used long-term precipitation records for Ireland, but these have been for a small number of stations and have lacked quality assurance of the underlying data. McElwain and Sweeney (2007) assessed long-term records at Birr and Malin Head from 1890-2003. Butler *et al.* (1998) conducted research on long precipitation records at Armagh dating back to 1838. Jones and Conway (1997) updated long records to produce area average precipitation data for the British and Irish Isles from 1840-1995. To date there has been no comprehensive research into long-term changes in precipitation at stations located across the Island of Ireland.

Using available long-term precipitation records previous research has shown that since the 1980s there has been a tendency towards wetter conditions across parts of Europe, the United Kingdom and Ireland (Todd *et al.,* 2015; Burt *et al.,* 2014; Met Éireann, 2016; Matthews *et al.,* 2016). However, most of these regions have also been affected by major drought periods in the past (e.g. Mac Cárthaigh,1996; Barrington, 1888; Marsh *et al.,* 2007; Lloyd-Hughes *et al.,* 2002; Todd *et al.,* 2013; Spraggs *et al.,* 2015;). These studies have produced important insights into past drought with some research highlighting the impacts from such extreme events.

Met Éireann classify an absolute drought as a continuous period of 15 days or more where less than 0.02mm of rainfall has fallen (Mac Cárthaigh, 1996). However, drought evolves slowly and can affect specific regions over short periods lasting weeks or persisting for longer periods from months up to several years or even decades. There are a number of definitions of drought; meteorological drought is described as continual deficits in rainfall amounts from the average rainfall, hydrological drought is based on the decline in surface and sub surface water supply from the average conditions, agricultural droughts are defined by soil moisture deficits which are crucial in crop growth (Mc Kee *et al.*,1995; Agnew, 2000; Keyantash and Dracup, 2002; Mishra and Singh, 2010). Lack of precipitation often cause both hydrological and agricultural droughts but other factors such as more intense but less frequent rainfall, extreme high temperatures, insufficient water management, soil erosion and bad agricultural practices can all enhance the drought event (Mishra and Singh, 2010).

While there has been some historical drought research in Ireland, most assessments have been limited to specific drought events. Barrington, (1888) provided one of the most detailed drought analysis for Ireland focusing on the severe drought of 1887. O Laoghog (1979) analysed the drought period of 1974-1976 using data from the Irish rainfall station network, while Mac Cárthaigh (1996) conducted a detailed analysis of the drought of 1995. Overall there is a scarcity of information on historical droughts and their spatial manifestation across the island of Ireland as well as a lack of understanding of the extent of impacts and responses of past society from such events.

Any changes in precipitation also impact on river flows causing issues with water supply, water quality and increased flood/drought risk. In Ireland, we also rely on river flows for hydro-electric power, water for agriculture, waste water treatment and for tourism activities such as fishing and boating (IAE, 2009). Ireland has a hydrometric monitoring network of over 800 gauging stations. But similar to rainfall the majority of good quality river flow records are short, only starting in the 1970s with some longer series from the 1940s (Murphy *et al.*, 2013). Another issue with many Irish catchments is that they have been affected by arterial drainage. In order to increase the productivity of agricultural land that was prone to ongoing flooding, arterial drainage schemes were implemented in many catchments across Ireland from the 1940s (King *et al.*, 2008). In many cases the post drainage rainfall runoff response is considerably different to the pre-drainage response which makes it difficult to analyse and can produce misleading results (Bhattaria and Connor, 2004; Harrigan *et al.,* 2014). Long river flow records are required in order to effectively detect changes, but this task is made difficult in Ireland due to the current paucity of long records (Murphy *et al.,* 2013).

Previous research in the UK has addressed the issue of short hydrological records by using reconstruction techniques (e.g. Jones, 1984; Jones *et al.*, 2006; Spraggs *et al.,* 2015; Lennard *et al.,* 2015). These studies used long precipitation records along with potential evapotranspiration (PET) data to drive hydrological models to simulate monthly river flow records as far back as the 18th century. The results from these studies have provided important insights into changes in river flow over the longer time scale.

1.1.1 Data rescue and historical records

The World Meteorological Organisation (WMO, 2014) has recently been implementing and supporting a global initiative to rescue historical meteorological, climatological and hydrological data. In many countries historical climate records have been meticulously kept in the past which has taken effort, time and resources. Hence, it is important that these records are effectively rescued, digitised and utilised. Global initiatives have also been formed with a focus on rescuing climate data such as The International Environmental Data Rescue Organization (IEDRO), The International Surface Temperature Initiative (ISTI) and the Atmospheric Circulation Reconstructions over the Earth (ACRE) project to name but a few.

Ireland has a rich history of weather record keeping dating back several centuries (Sweeney, 2014). However, early organised weather record keeping only began in Ireland at the end of the 18th Century. Stations were typically located in astronomical observatories at Dunsink (1788), Armagh (1790), Markree (1824), and Birr (1845) with the National Botanical Gardens (1800) and Phoenix Park (1829) in Dublin also recording early weather data. By 1860, as part of the British Meteorological Office network, Valentia Island station transmitted the first weather observations to enhance storm warnings for ships (Sweeney, 2014). During the late 19th and early 20th century daily observations on rainfall, cloud cover, sunshine and temperature as well as storminess and atmospheric pressure were regularly recorded at stations located throughout Ireland. Many of the observers were volunteers and were dedicated to recording regular continuous observations, many spanning several decades. The weather readings were taken at least once a day usually at the same time early in the morning, written on broad sheet sized forms and regularly posted to the British Meteorological office for centralised compilation. The annual Symons and British rainfall books published monthly summaries from all the network stations along with useful statistics and analysis.

Figure 1.1: Hard copies of rainfall records held in Met Éireann archives (Photos taken by S.Noone, 2012)

The Irish Meteorological Service (Met Éireann) was formed in 1937 to provide weather information for the growing transatlantic aviation industry, with the majority of digitised Irish climate records available from 1941 (Sweeney, 2014). Some of the original hard copy archived Irish weather records were held in the British Meteorological Office up to the 1980s when they were returned to Met Éireann (See Figure 1.1). These hard copy paper records contain both daily and monthly rainfall observations taken during the 19th and early 20th century and provide a wealth of information about past climate in Ireland.

Figure 1.2: Map showing the existing long-term precipitation records denoted by black triangles and the black circles represent the stations with long-term hard copy monthly precipitation records held in Met Éireann archives identified for transcribing.

These historical precipitation records have been in some cases the life work of the observers. Therefore, it is crucial that these records are rescued, quality checked and utilised to increase understanding of Ireland’s past climate. Permission has been obtained from Met Éireann for this study to access these historical hard copy records to identify, digitize and rescue suitable long station precipitation records. The stations with long-term monthly precipitation records identified for transcribing are shown in Figure 1.2 and are represented by black circles, with the existing long-term precipitation records denoted by black triangles. Note that for the rest of this thesis the term *long-term* refers to the entire period of observations at a given station.

1.1.2 Thesis key aims

The overarching aim of this thesis is to rescue and transcribe hard copy long-term monthly precipitation records for the island of Ireland adding to the existing series. To quality check and assess the long-term precipitation records for variability and change and analyse the records to identify past drought events. In addition, this thesis aims to integrate past documentary evidence into the analysis to add confidence to the data and present some of the social economic impacts from past drought events. To reconstruct long-term river flow records utilising the good quality monthly precipitation records and asses the flow for past drought events.

1.2 Thesis structure

A detailed literature review that develops the research gaps is presented in **chapter 2**. The transcribing and data rescue methods using hard copy archived monthly precipitation records are presented in **chapter 3**. The same chapter presents methods used for homogenisation and quality assurance of the raw data together with an analysis of an expanded long-term monthly precipitation network for Ireland for the period 1850-2010. The identification and assessment of historical drought across this long-term network is presented in **chapter 4** along with details of socio-economic impacts and responses derived from newspaper records. **Chapter 5** presents the river-flow reconstructions for selected study catchments and subsequent analysis of low flow and drought periods. Discussion of results, research limitations, priorities for future work and final conclusions are presented in **chapter 6**. Figure 1.2 provides a schematic of the thesis structure and workflow.

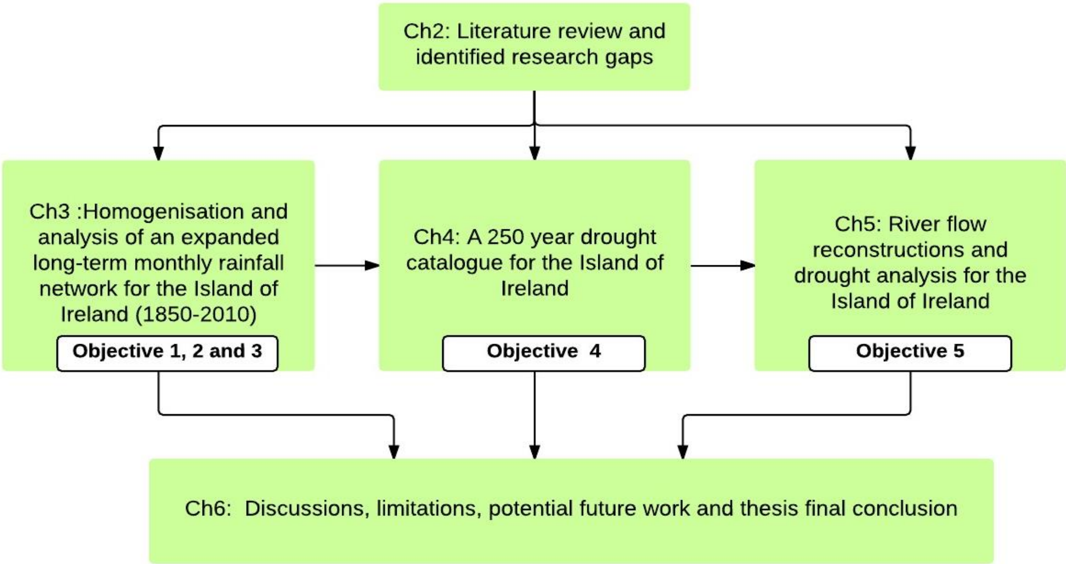

Figure 1.3 Workflow of thesis research showing each thesis objective and subsequent chapter

During the 3 years of this PhD research I was involved in the following peer reviewed publications as either lead author or as collaborating senior author.

Noone S, Broderick C, Duffy C, Matthews T, Wilby RL, Murphy C. 2016. A 250 year drought catalogue for the island of Ireland (1765-2015) *Int. J. Climatol.* Accepted with minor corrections.

I was lead author on this paper and I developed the study design, conducted all the data collection and analysis as well as compiling all metadata. I also wrote up the text with the help of suggestions and comments from my co-authors.

Murphy C, **Noone S**, Duffy C, Broderick C, Matthews T, Wilby RL. 2016. Irish droughts in newspaper archives: Rediscovering forgotten hazards? *Weather.* Accepted.

I was second author on this paper but my contribution was limited to helping with source material, some research and comments on the draft manuscript.

Wilby RL, **Noone S**, Murphy C, Matthews T, Harrigan S, Broderick C. 2015. An evaluation of persistent meteorological drought using a homogeneous Island of Ireland precipitation network. *Int. J. Climatol.* doi:10.1002/joc.4523

I was second author on this paper but my contribution was limited to helping with source material, some research and comments on the draft manuscript.

Noone S, Murphy C, Coll J, Matthews T, Mullan D, Wilby RL, Walsh S. 2015. Homogenization and analysis of an expanded long-term monthly rainfall network for the Island of Ireland (1850–2010). *Int. J. Climatol.* doi: 10.1002/joc.4522.

I was lead author on this paper and I developed the study design, conducted all the data collection and analysis. I also wrote up the text with the help of suggestions and comments from my co-authors.

Chapters in this PhD thesis are comprised of two of these publications; chapter 3 (Noone *et al.*, 2015) and chapter 4 (Noone *et al.*, 2016). The discussion draws on my contributions to Murphy et al. (2016). Many of the ideas and components for all of these publications stem from the research undertaken as part of this PhD.

2 Literature review

2.1 Introduction

This chapter identifies the key research gaps that will be addressed by this research. The literature review will highlight the significance of long-term climate records, the importance of data quality assurance and the value of integrating documentary sources to provide evidence of past climate change. The chapter is organised as follows. Section 2.2 provides a literature review on long-term changes in precipitation in Europe, the United Kingdom (UK) and Ireland; Section 2.3 outlines previous work on data homogenisation; Section 2.4 reviews previous research on changes in river flow; Section 2.5 discusses previous work on historical drought; Section 2.6 reviews previous research that highlights the value of integrating documentary evidence into the analysis of past observations before research gaps are identified in Section 2.7.

2.2 Long-term changes in precipitation

In understanding how climate change signals are manifested, or not, increased focus is being placed on the detection and attribution of change in observational records to provide an evidence base for adaptation planning and investment (Hannaford and Marsh, 2006; Wilby *et al.,* 2008; Murphy *et al.,* 2013; WMO, 2014). Long-term precipitation records are often difficult to acquire, but are important for the accurate detection of change (Jones, 1984; Burt *et al.,* 1998; Bayliss *et al.,* 2004; Barker *et al.,* 2004; Jones *et al.,* 2006; Wilby, 2006; De Jongh *et al.,* 2006; WMO, 2014). These issues are of particular importance where risks from extremes such as floods and droughts have the potential to impact adversely on society with potentially high costs for communities, critical infrastructure and the economy.

Early studies have used data rescue/recovery methods to produce long-term observed precipitation series across Europe. Tabony (1980) constructed series for 185 stations in Europe dating from 1861, or earlier, to 1970. The study constructed continuous monthly rainfall series for such countries as Italy, UK, Sweden and Poland and included 17 stations for Ireland. Tabony (1980) employed several sources such as the many European meteorological service monthly weather reports, the 10 year UK Meteorological Office books and data from many other European Meteorological Services. In quality assuring records the study collected and grouped precipitation records from a number of stations within 30 km of candidate stations (Tabony, 1980). Using an overlapping data period these records were corrected annually using appropriate ratios and weights. Detailed metadata was also obtained for each station along with comprehensive information on historical rainfall observations (Tabony, 1980). Briffa (1984) added to the Tabony (1980) series by producing some long-term precipitation data using multiple linear regressions with tree ring widths from oak trees. The main objective of this study was to demonstrate the potential usefulness of tree rings as a source of past hydro-climatic information. The archive of long-term precipitation series for the UK and Ireland is available from the Climate Research Unit (CRU) at the University of East Anglia.

2.2.1 Long-term changes in precipitation across Europe

Studies across European regions have focused on long-term climate data rescue and analysis (Auer *et al.,* 2005; Pauling *et al.,* 2006; Brunet and Jones, 2011; Brunet *et al.,* 2013). Auer *et al.,* (2005) developed an instrumental precipitation dataset for the Greater Alpine region for the period 1800-2002 using archive observations. These records were quality checked by comparison with neighbouring series, with over 2500 issues and 5000 outliers discovered and removed from the 557 precipitation series. Analysis of this benchmark precipitation network show significant regional and seasonal variations with increases in precipitation for northwest Europe and decreases in the southeast over the period 1800-2002 (Auer *et al.,* 2005). Similarly, Brunet *et al,* (2013) identified, digitized and quality checked historical temperature and precipitation observations at 79 stations from hard copy log books. The data series covered the Mediterranean North Africa and Middle East regions with some records starting in the late 19th century.

Moberg *et al.* (2006) in a study of daily temperature and precipitation extremes across Europe for the period 1901-2000 found that winter precipitation totals have significantly increased (0.05 level) by 12% over past 100 years. The same study found that summer precipitation indicates weak decreasing trends. However, it was also noted that due to data inhomogeneities and sparseness of some records across specific regions of Europe the robustness of these conclusions are somewhat weakened (Moberg *et al.,* 2006).

Longobardi and Villani (2010) utilized long-term precipitation observations over the Mediterranean region to conduct a trend analysis for the period 1918-1999. Their results showed some statistically significant negative trends in both annual and seasonal precipitation, except for summer where positive trends were present. For Belgium precipitation records spanning 105 years were employed to detect changes in seasonal and annual trends with wavelet analysis conducted on the series. Statistically significant trends were found in both annual and winter totals but trends over shorter time periods were not representative of the trends in longer records (De Jongh *et al.,* 2006). De Lima *et al.* (2010) showed that since the 19th century trends in annual and monthly precipitation totals over Portugal have not changed, but the tests were also sensitive to the period of analysis with statistically significant trends weakening and strengthening over partial periods. The study noted that short precipitation records over only several decades can introduce bias by the period of study (De Lima *et al.,* 2010).

2.2.2 Integration of documentary evidence into research

Several studies have utilised documentary sources combined with observations to reconstruct past climate records. Brázdil (1996) used historical documentary evidence about weather phenomenon to assess seasonal and annual decadal temperature and precipitation totals over the past 500 years in the Czech Lands. Results indicate that much colder and wetter conditions prevailed in central Europe between the 15th and 17th centuries and again in the 19th century (Brázdil, 1996). Research by Pfister (1999) used documentary data to reconstruct seasonal and annual precipitation and temperature in Central Europe in the 16th century. The results of this study provide important insights into past climate variability while highlighting impacts from past extreme weather events (Pfister, 1999). Research by Dobrovolný *et al.* (2015) employed documentary based precipitation indices and observations to reconstruct seasonal and annual precipitation in the Czech Lands from AD 1501. Results showed that the highest precipitation totals occurred during the 16th century, with the driest 30-year period occurring during the 18th century. The driest year and driest summer season was identified as 1540 with the wettest year occurring in 1515 (Dobrovolný *et al.,* 2015). Further research reconstructed both temperature and precipitation for central Europe back to 1500 using documentary sources and observations (Brázdil *et al.,* 2016). Results showed a cluster of driest years occurred during the start and end of the 18th century and 1540 is also highlighted as being the driest year since 1500 (Brázdil *et al.*, 2016).

Rodrigo and Barriendos (2008) analysed seasonal and annual precipitation over the Iberian Peninsula using data spanning the past 400 years. The authors reconstructed rainfall records using a combination of observations and documentary sources. Results show changes in seasonal and annual anomalies when compared to the 1961-1990 baseline (Rodrigo and Barriendos, 2008). In addition, significant dry periods were identified for the Iberian Peninsula in 1529, 1541, 1628, 1631, 1701, 1725, 1788 and 1821. The study also noted that much dryer conditions were experienced during the 18th century. The results were validated using proxy data, different data sources and data from neighbouring regions (Rodrigo and Barriendos, 2008). Documentary evidence was also employed by Kjeldsen *et al.* (2014) to identify historical flood events in European countries. The study concluded that there is considerable potential for integrating information from historical documentary data sets to improve the reliability of current flood risk assessments (Kjeldsen *et al.*, 2014).

Casty *et al.* (2005) reconstruct a high resolution (0.5º x 0.5º) monthly and seasonal temperature and precipitation gridded data sets for the European Alps (1500-2000). The study used instrumental observations for temperature and precipitation at sites across Europe and integrated several documentary records and proxy sources to use as predictors in producing the gridded data set. The study also incorporated data detailed in Mitchell *et al.* (2004) for the period 1901-2010. Findings show that winter and summer temperatures indicate a change from much colder conditions prior to 1900 to warmer conditions in present times (Casty *et al.*, 2005). The years of 1540, 1921 and 2003 stand out as the driest years in the Alpine region over the past 500 years (Casty *et al.*, 2005). The North Atlantic Oscillation correlated negatively with precipitation reconstructions but positively with temperatures during winter, but noted that correlations were temporally unstable (Casty *et al.*, 2005).

Pauling *et al.* (2006) used similar techniques to Casty *et al.* (2005) in reconstructing five hundred years of gridded high resolution precipitation across Europe. The study used a selection of long precipitation observations, precipitation indices from documentary sources, tree rings, ice cores, corals and speleothems (cave deposits) (Pauling *et al.,* 2006). This study used transfer functions over a calibration period 1901-1983 and applied them to the period 1500-1900 to produce a gridded precipitation dataset for Europe. The results highlighted large inter-annual and decadal fluctuations in precipitation reconstructions. The study also found that the winter of 1774, spring 1886, the summers of 1666 and 1669 and autumn 1669 were the driest seasons in the past 500 years (Pauling *et al.,* 2006). Casty *et al.* (2007) used independent reconstructed gridded temperature, precipitation and 500hPa geopotential height data spanning the last 235 years to assess the climate variability and spatial and temporal evolution of these variables for Europe. Results of this study found that the influence of the (NAO) is more prominent for winter, spring and autumn with a positive trend detected during the past 40 years for spring and winter NAO (Casty *et al.,* 2007). Seasonal European temperatures show increasing trend mostly over the past 40 years with highest values since 1766. The results indicate no trend present in precipitation (Casty *et al.,* 2007).

2.2.3 The North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is the main influencing factor on the variability of the climate across much of Europe and in particular the island of Ireland and UK (Visbeck *et al.,* 2001; Pinto & Raible, 2012) Studies have found a correlation between a positive NAO and increased precipitation during winter and spring, with a negative correlation during the summer following a NAO positive winter in Ireland (Kiely, 1999; Murphy and Washington, 2001 McElwain and Sweeney, 2003; Wang *et al.,* 2006; Leahy and Kiely 2010; Noone *et al.,* 2015).

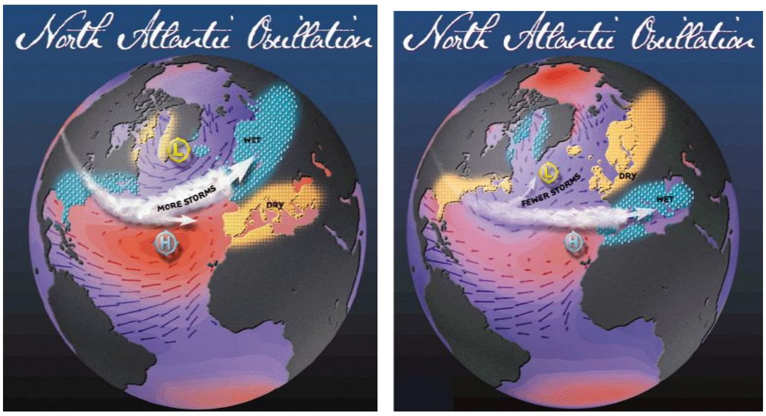

Figure 2.1 Illustrations of NAO positive phase (left) and NAO negative phase (right) Source (http.//www.ldeo.columbia.edu/res/pi/NAO/**)**

The NAO is an atmospheric phenomenon explained as a barotropic teleconnection pattern or spatial oscillation in the troposphere over the Northern Atlantic European region (Pinto and Raible, 2012). The NAO is characterised as being in a positive phase when an intensified Azores high to west of the Canary Islands and a deeper low is present off the coast of Iceland. The positive NAO phase causes a strong meridional pressure gradient in the atmosphere over the North Atlantic Ocean. This causes a stronger moist westerly weather types over the continents situated in the northern region of the Atlantic (Sweeney, 1998), leading to much more unstable weather conditions and increased rainfall over Ireland (Figure 2.1). In contrast to the warmer and wetter conditions experienced over Northern Europe much dryer conditions can be seen over southern parts of Europe along the Mediterranean (Visbeck *et al.,* 2001; Pinto and Raible, 2012). A negative phase of the NAO is classified with a weaker Azores high and a shallower Icelandic low (Figure 2.1). The meridional pressure is reduced and less intense westerly airflow is directed across the north Atlantic and Western Europe (Pinto and Raible, 2012). An NAO negative phase tends to be associated with more unstable wetter weather over southern Europe. Across northern Europe there is a tendency for much dryer, colder and stable conditions remaining for several weeks, caused by the blocking stationary high spanning across eastern, western and central Europe (Pinto and Raible, 2012).

2.2.4 Long-term changes in precipitation across the United Kingdom (UK)

The long-term CRU precipitation records originally produced by Tabony (1980) have subsequently been updated and used in several studies to analyse long term rainfall for the UK. These studies have produced important insights into historical extremes and changes in variability (e.g. Jones, 1983; Gregory *et al.,* 1991; Jones and Conway, 1997; and Burt *et al.*, 2014). Jones and Conway (1997) constructed area average precipitation by updating the CRU data for an England and Wales precipitation series (EWP) 1766-1995. The same study updated and produced a precipitation series for Scotland and Northern Ireland 1760-1995, with a new precipitation series developed for Ireland 1840-1995. Results of this study showed that 1995 was the driest summer on record for the UK, but was not as severe for Ireland and Scotland (Jones and Conway, 1997). Results for the EWP series 1766-1995 suggest little or no trend for spring, weak decreasing trends for summer and autumn but increasing trends for winter (Jones and Conway, 1997). The precipitation series for Scotland 1757-1995 shows significant increases in precipitation during winter and spring over the recent 5-10 years, with decreases in summer and autumn precipitation. The results for Ireland 1840-1995 show that inter-annual variability is lowest during spring and greatest during autumn, with no changes present for winter or summer (Jones and Conway, 1997). The study noted that the recent increases in winter and spring precipitation since 1985 are associated with a positive phase of the North Atlantic Oscillation (NAO).

Research for the UK used the CRU long-term precipitation archive from 1880-1997 and highlighted periods of drought and changes in seasonality (Burt *et al.,* 1998). The results also show that wetter winter and drier summer periods were associated with phases of positive and negative NAO. Alexander and Jones (2001) employed the long-term monthly precipitation series for the UK (1766-2000). Findings showed trends towards drier summers in the southeast of the UK and wetter winters in the west of Scotland (Alexander and Jones, 2001). The same study identified that April 2000 was the wettest since records began in 1766; results also contextualised the extreme precipitation for autumn 2000.

Barker *et al,* (2004) constructed a 200-year precipitation index for the English Lake District. The study used a seasonal regression technique for overlapping data periods from different stations to extend contemporary records back to 1788. Analysis of the derived series showed a significant decrease in summer precipitation since 1960, with increases in winter and spring which counteracted any summer decreases on an annual basis. The results of the same study identified several notable periods of prolonged drought in the early records during the 1850s, 1880s, 1930s and 1970s. Several prolonged wet periods were also identified during the 1820s, 1870s, 1920s, 1940s and 1990s (Barker *et al.,* 2004).

More recently Burt *et al,* (2014) produced an updated analysis of the CRU archive monthly precipitation series for the UK focusing on the 1870s decade. The study compared precipitation during the 1870s with the recent wet years/seasons including 2012 and winters of 2013/14 to contextualise these extremes. In addition, Lamb weather type counts and the NAO index were used to classify specific conditions during these particularly wet periods (Burt *et al.,* 2014). Results showed that during 1872, 1876 and 1877 extremely high precipitation totals for the lowlands of the south and east were associated with a high frequency of cyclonic weather types. The results also found that strong westerly airflows are important for high precipitation at upland and northwest coastal locations (Burt *et al.,* 2014). Work by Todd *et al.,* (2014) constructed a composite precipitation series for Carlisle in the northwest of the UK for the period 1757-2012. The study used overlapping periods of records and seasonal linear regression and adjustment techniques to construct the continuous composite series. Results of the analysis of the constructed long precipitation series revealed statistically significant positive trends in winter precipitation over the period of record. The study identified the wettest years as; 1768, 1839, 1877, 1900, 1903, 1916 1954, 1967, 2008 and 2012. The results also showed the driest years as; 1784, 1788, 1855, 1870, 1933, 1955, 1996, 1989, 2003 and 2010 (Todd *et al.,* 2014).

2.2.5 Long-term changes in precipitation across the Island of Ireland

There has been limited research assessing long-term variability and change in precipitation for Ireland. Grew (1951) compiled and quality assured rainfall observations at Armagh Observatory. This study found some issues due to gauge changes and position moves in some years. In addressing these errors the study used correction factors and adjustments by comparing overlapping gauges to produce a high quality homogenous series 1838-1950. The same report also presents historical information on rainfall and extremes experienced at Armagh and compiled some very useful metadata and a station history (Grew, 1951). Adding to this work Butler *et al.* (1998) analysed updated precipitation records for Armagh Observatory in Northern Ireland from 1838-1997. Results reveal variations in the distribution of rainfall throughout the year and indicate that this station has been experiencing much drier summers in recent decades (Butler *et al.,* 1998). The same study also found a strong correlation between winter and autumn precipitation and the corresponding NAO index. Summer precipitation indicates a non-significant negative correlation with the previous winter NAO index (Butler *et al.,* 1998).

Previous research in Ireland by McElwain & Sweeney (2007) analysed long-term monthly precipitation records from 1890-2003 at Birr and Malin Head. Results showed no trend present in annual precipitation at Birr, but significant increasing trend in annual precipitation at Malin Head (McElwain & Sweeney 2007). More recently Matthews *et al.,* (2016) employed long-term Irish precipitation records developed in this work for 1850-

2015 to examine the changing likelihood of extreme seasonal conditions. In addition, the same study explored how frequently these extremes might occur in the future based on the latest model projections. The results indicate the likelihood of the wettest winter (1994/95) and driest summer (1995) has doubled since 1850 respectively (Matthews *et al.*, 2016). The results also show that the most severe end-of-century climate model projects indicate that the occurrence of wet winters like 1994/95 and summers as dry as 1995 may increase by factors of 8 and 10 respectively by the end of the century (Matthews *et al.*, 2016).

2.3 Homogenisation and data quality assurance

The reliability and quality of precipitation data depends on many factors, as inhomogeneity can arise due to changes in methods of instrumental data collection, conditions of the site, reliability of measurements or site relocation. The majority of records have been affected by non-climatic issues, which make the identification of climatic variations difficult (Peterson *et al.*, 1998). Therefore, it is important that the data series is homogenous (Peterson *et al.*,1998; Wijngaard *et a*l., 2003; Dhord & Zarenistanak, 2013). A homogenous series can be defined as a series that is only influenced by climatic variation. Any inhomogeneities in the climate series can interfere with the detection of legitimate climate change signals and can cause poor climatic or impact model calibration or biased trends and variability results (Beaulieu *et al.*, 2009**)**. Therefore, the detection and correction of all inhomogeneities in a series is crucial prior to conducting analysis.

Homogeneity tests can be broadly classified as “absolute” and “relative” methods. Absolute methods are applied to individual stations to identify statistically significant breaks in the data. Wijngaard *et al.* (2003) and Dhorde and Zarenistanak (2013) applied a combination of multiple absolute tests to detect breaks in both rainfall and temperature records. The four methods employed were: the standard normal homogeneity test (SNHT) for single break (Alexandersson, 1986), the Buishand range test (Buishand, 1982), the Pettitt test (Pettitt, 1979) and the Von Neumann ratio test (Von Neumann,1941). The SNHT detects breaks near the beginning and the end of a series, the Buishand range and the Pettitt tests are more sensitive to breaks in the middle of a series (Wijngaard *et al.*, 2003). The results of all tests were evaluated and classified based on the number of tests that rejected the null hypothesis (no break detected). The next step verified the breaks by scrutiny of available station metadata, which is crucial in all homogeneity tests (Wijngaard *et al.,* 2003).

Relative methods incorporate correlated neighbouring stations for comparison with a station of interest to test for homogeneity. Reference series or reference sections are used in detection procedures in many homogenisation methods, (WMO, 2011), as well as being used to assess the quality of the homogenisation (Kuglitsch *et al.,* 2009). These reference series need to experience the same climate influences as the candidate station (Szentimrey, 1999; Zhang *et al.,* 2001; Causinus and Mestre, 2004; Della-Marta and Wanner, 2006; WMO, 2011). However, issues can arise in the homogenisation process when correlated stations also contain inhomogeneities with more than one break detected (Lindau and Venema, 2013). Moreover, if simultaneous changes in the measuring technique occur within a region the relative tests are no longer practical, as all series are affected at the same time and absolute methods should be employed (Peterson *et al.,* 1998; Wijngaard *et al.,* 2003). Detailed metadata and station history are critical in evaluating identified breaks; otherwise correcting issues within the records is not an informed decision. Relative testing can be a more reliable and robust method of checking for breaks in data once the station records are highly correlated (Wijngaard *et al.,* 2003).

Many approaches have been developed to identify and adjust inhomogenities in climate data. Most of these methods use relative techniques which involves comparison between a candidate series and a reference series. Alexanderson and Moberg (1997) developed a new relative test for detection of linear trends in normally distributed time series. The test detected and estimated gradual and abrupt changes in the mean of a candidate series compared with a homogenous reference series (Alexanderson and Moberg 1997). Other pioneering work in data homogenisation includes the methods developed by Jones *et al.,* (1986) and Karl and Williams (1987).

Jones *et al.* (1986) compiled a new monthly mean surface air temperature dataset for the Northern Hemisphere 1851-1984. The study analyzed the data to assess homogeneity and corrected issues using relative homogenisation techniques (Jones *et al.,* 1986). Further research by Karl and Williams (1987) used the concepts of relative homogeneity and standard parametric tests for temperature and non-parametric statistics for precipitation to identify and adjust any inhomogeneities.

In building on previous work (e.g. Jones *et al.,* 1986; Alexandersson and Moberg, 1997; Karl and Williams, 1987) several new techniques have been developed for break detection and adjustment of non-climatic inhomogeneities (Cao and Wan 2012; Toreti *et al.,* 2012; Freitas *et al.,* 2013; Mestre *et al.,* 2013). A comprehensive analysis to assess different homogenisation methods was included in the scientific programme of the COST Action HOME ES 0601: Advances in Homogenisation Methods of Climate series: an integrated approach (HOME). The HOME objective was to develop a general homogenisation method for homogenising climate and environmental datasets. This programme commenced in 2007 and was finalised in 2011 with the release of two new software packages, HOME-R (HOMER) software package for the homogenisation of monthly data and HOM/SPLIDHOM for daily data homogenisation (HOME, 2013).

2.4 Past changes in river flow

Changes in the hydrological cycle at a global scale have been detected and are very likely due to rising human induced concentrations of atmospheric GHG's (Wilby, 2006). Although flood and drought periods have been detected in historic river flows in the UK no underlying trends have been detected (Wilby, 2006). The lack of long-term river flow records makes it difficult to detect climate change signals because of the weak signal to noise ratio when considered against the greater year to year variance of river flows (Kundezewicz *et al.,* 2005). In addition issues can arise in river flow observations which can cause gradual changes in the observations. Factors such as weed-growth, sedimentation, erosion, or works carried out on the channel or floodplain can all influence the records and create inhomogeneities (Kundzewicz and Robson 2004; Svensson *et al.,* 2005; Fowler and Wilby, 2010).

Other issues in hydrometric records can arise from arterial drainage schemes, land use change, water abstraction, water storage, diversion, and discharge (Bhattaria and Conor, 2004; Kundzewicz and Robson 2004; Hannaford and Marsh, 2006; Murphy *et al.,* 2013).

Arterial drainage is particularly problematic in Ireland as extensive arterial drainage schemes were conducted across many catchments since the 1940s to increase agricultural land and to alleviate flooding (Murphy *et al.*, 2013).

Due to the large uncertainties associated to climate change impact studies there is a need to fully understand how climate change signals evolve or not in hydrometric observations (Hannaford and Marsh, 2006; Whitfield *et al.,* 2012). An increasing number of countries are making investment in producing Reference Hydrometric Networks (RHNs) to collect hydrometric data that are only minimally affected by human influence (Stahl *et al.,* 2010; Whitfield *et al.,* 2012; Murphy *et al.,* 2013). Bradford and Marsh (2003) produced a network of benchmark catchments for the UK to improve the ability to identify and interpret hydrological trends throughout the UK. The benchmark network consists of 120 undisturbed near natural catchments with good quality hydrometric data. Murphy *et al.*, (2013) developed an Irish Reference Network (IRN) of hydrometric gauges to monitor and detect climate driven trends. This work identified 43 hydrometric stations across the Island of Ireland (IoI) with catchment sizes ranging from 65 to 2460 km^2 with the average record length of 40 years, the longest being 63 years. Key criteria for inclusion of gauging stations in the IRN were based on international RHN standards (Murphy *et al.,* 2013) and include:

- Good consistent hydrometric data (particularly for extreme low flow) as well as stable accurate rating curves.
- Near natural flow regime with either zero or stable water abstractions (impact less than 10% of flow or in excess of Q95)
- Long records (minimum 25 years).
- Limited land use influence, stations with arterial drainage where excluded where possible, post drainage records were also used to increase spatial coverage.
- Stations needed to be representative of Irish hydrological conditions with good spatial coverage (Murphy *et al.,* 2013).

Utilising the RHN of near-natural catchments in the UK Hannaford and Marsh (2006) applied trend tests to time series of runoff and low flow indicators (1963-2002). The results show that low-flows have been relatively stable since the early 1960s (Hannaford and Marsh, 2006). In addition, runoff for catchments in Scotland showed the strongest positive trend, with some increases in runoff at western maritime catchments across Wales and UK (Hannaford and Marsh, 2006). The same study analysed some long-term hydrometric records at catchments located in North Wales, East Scotland (1940-2002) and the River Thames in southeast England (1880-2002). All three catchments showed increases in annual runoff over various periods, with only the Thames showing significant positive trend in annual runoff (Hannaford and Marsh, 2006).

Stahl *et al.* (2010) investigated near-natural river flow trends from 441 small catchments in 15 countries across Europe since 1932. Results suggest positive trends in winter at most catchments, with a shift towards negative trends from April to August. The same study found that low flows have decreased in most regions where the lowest mean flow occurs in summer; with results varying at catchments where lowest flow occurs in winter (Stahl *et al.*, 2010). In addition, results indicate that annually river flows across southern and eastern regions are decreasing, with positive trends in annual flow elsewhere (Stahl *et al.*, 2010).

Hannaford and Buys (2012) analysed a network of near natural catchments across the UK 1969-2008. Results show a high degree of spatial variability in seasonal trends. The results indicate that winter flows in upland and western areas have increased, with autumn flows showing increases in most catchments across the UK. The study also found weak decreasing trend in spring flows mainly in lowland catchments, with no summer trend identified in any catchments (Hannaford and Buys, 2012). Hannaford (2015) found increases in high flow magnitude and duration at catchments in the north and west of the UK. Studies in the UK have not found any evidence for long-term increase in flooding. However, results do indicate a high degree of inter-annual variability with notable flood-rich and flood-poor periods in long UK hydrological records (Hannaford, 2015; Wilby and Quinn, 2013). Most studies have focused upon flooding with much less work on changes in low flows or drought (Watts *et al;* 2015). Similar to floods, low flow or drought show marked inter-decadal variability in long records. However, a number of droughts in the 19th century were much longer and more severe than those experienced in the 20th century (Marsh *et al.*, 2007).

Some studies have addressed the issue of a lack of long hydrometric records. Jones (1984) utilised long-term precipitation records to reconstructed river-flow records for the UK dating back to 1844. The study used a rainfall runoff model that relates the logarithm of mean monthly river flow to linear permutations of recent monthly soil moisture and effective rainfall (precipitation minus actual evapotranspiration) and stream-flow records to establish a relationship using multiple regression analysis. The advantages of such a simple model are that it is easy to calibrate and then to validate the model over an independent period to assess the performance. The reconstructed river flow data is useful for low flow research, but not for assessing potential flood events due to the monthly time scale (Jones, 1984). In addition, the reconstructed records can be used for water system management. Results of this research indicate drought rich periods during 1925-1979 with this period three times more likely to have experienced extreme drought when compared to the period 1870-1924 (Jones, 1984).

The research by Jones, (1984) was subsequently updated by Jones and Lister (1998) up to the mid 1990s and by Jones *et al.* (2006) to 2002. The latter study assessed recent hydrological droughts and compared them over the long-term context back to 1860. Results showed that the low flow periods of 1984, 1989 and 1995 rank in the top 5 lowest flows since 1865 across some catchments. However, the drought years 1870, 1887, 1921, 1933/4 and 1976 were more spatially widespread (Jones *et al.,* 2006). However, some factors need to take into account when producing reconstructed river flow data. Firstly, it is important to obtain good quality homogenous rainfall records within or close to the catchment of choice. Secondly the use of constant monthly values of evapotranspiration along with the potential influence of snow during colder periods can cause modelling output errors. Furthermore, changes to land use or other artificial influences can alter the regression relationship over time especially if they coincide with chosen calibration or verification periods. Finally, the quality of observed river gauges records or any change in location will affect the accuracy of the calibration/verification of the model (Jones *et al.,* 2006).

Wilby (2006) analysed the homogeneous rainfall and river flow reconstructions (1865-2002) originally produced by Jones *et al.,* (2006) at 15 catchments across the UK. The study investigated the relationship between the strength of the trend and the detection time at seasonal and annual time scales. Results indicate significant increases in winter and decreases in summer precipitation, the same results are found for river flow (Wilby, 2006). The same study also noted that as the record length is reduced the summer trends tend to weaken, with no such change in annual totals (Wilby, 2006). Burt *et al.,* (1998) investigated changes in rainfall and river flow from 1880-2000 for the north central region of the UK, with results indicating increases in recent variability with the winter to summer contrast becoming larger for runoff and rainfall (Burt *et al.,* 1998).

In Ireland, there has been limited research into changes in river flow over the longer time scale, which is due to a lack of continuous long term observational records. Since the mid 1970s research in Ireland has found increasing trends in annual precipitation which also correlates with a shift towards a more positive phase of the (NAO) around this time (Kiely, 1999; Sheridan 2001; McElwain and Sweeney, 2003). Research by Kiely (1999) found that river flow at four Irish catchments also experienced a significant step change in annual flow in the mid-1970s. The study found that since 1975 the increases in river flow were greatest across the west of Ireland, which would correspond with an increase in westerly airflow due to the positive NAO. The results for the river Boyne for the period 1958-1995 were particularly significant, with large increases in both annual and March flows around the mid-1970s. This study concluded that the positive NAO was the main driver of these changes in Boyne river flow (Kiely, 1999). However, issues were highlighted in a more recent a study by Harrigan *et al.* (2014) on attribution of detected changes stream flow which found that major arterial drainage works carried out on the Boyne catchment in 1970s and early 1980s was the main driver of change in annual mean and high flows.

Murphy *et al.* (2013) applied the Mann-Kendall and Thiel Sen trend tests to eight hydro climatic indicators at 43 flow gauges in the IRN, firstly over a fixed period and then for varying start and end dates. Results suggest that the detected trends are similar to rainfall indicating that they are climate driven. However, the large temporal variability makes it difficult to detect anthropogenic climate change signals. The trend results for summer and winter are contrary to what would have been expected due to anthropogenic climate change (Murphy *et al.,* 2013). The study found widespread decreasing trends in mean winter flow records over the shorter period with a tendency towards more positive trends in longer records. Results also showed that when influential extreme values at the start and end of summer flows were removed no evidence of decreasing trends were found (Murphy *et al.,* 2013). There were strong increasing trends in high flow indicators which may be useful for early detection of climate signals. The study noted that caution should be taken when conducting trend analyses on flow records over fixed periods when these may be dominated by weak signals, greater variability and non-stationarity (Murphy *et al.,* 2013). Hall (2013) conducted analysis on low flows at catchments in the IRN. The study found it difficult to distinguish between real long-term changes and medium to long-term natural variability due to lack of long-term records. The study also noted that further research is needed to understand the increasing trends in low flow indicators for summer in the IRN (Hall, 2013). Trend results also highlighted the danger of interpreting trends over shorter fixed periods, as results showed that trends are highly dependent on the period selected (Hall, 2013).

2.5 Drought analysis.

Drought is a regularly occurring natural hazard across much of Europe and causes significant socio-economic and environmental impacts (Lloyd-Hughes and Saunders, 2002; Marsh *et al.,* 2007; Lennard *et al.,* 2014). Drought evolves slowly and can affect specific regions over short periods lasting weeks or may persist for longer periods from months up to several years or even decades. There are a number of definitions of drought; meteorological drought is described as continual deficits in rainfall amounts from the average, hydrological drought is based on the decline in surface and sub surface water supply from average conditions while agricultural drought is defined by soil moisture deficits which are crucial in crop growth (McKee *et al.,* 1993; Agnew, 2000; Keyantash and Dracup, 2002). Lack of precipitation often causes both hydrological and agricultural droughts, but other factors such as more intense but less frequent rainfall, extreme high temperatures, insufficient water management, soil erosion and bad agricultural practices can all enhance the drought event (Mishra and Singh, 2010; Dai, 2011; Jenkins and Warren, 2015).

Recent decades have seen some extreme drought events across the UK and parts of Europe most notably 1975-1976, 2003, 2004-2006 and 2010-2012 (Fink *et al.,* 2004;

Marsh, 2004; Todd *et al.*, 2013; Lennard *et al.*, 2014; Spinoni *et al.*, 2015;). Impacts from these extreme events have been a reduction in water supply and hydro-electric power generation, environmental damage, and health issues (Cole and Marsh, 2006; Briffa *et al.,* 2009; Hannaford *et al.,*2011; Lennard *et al.,*2014). In light of the potential issues for water resource management numerous studies have been conducted across Europe and the UK focusing on the long-term to improve understanding of past drought events and assess their impacts (Mishra and Singh, 2010; Gosling *et al.,* 2012; Watts *et al.,* 2014; Lennard *et al.,* 2014; Lennard *et al.,* 2015; Kingston *et al.,* 2015; Spraggs *et al.*, 2015). Bradzil *et al.* (2013) used various historical documentary sources along with instrumental data to reconstruct historical droughts for the Czech Lands from 1090-2012. The study found several historic severe drought events while noting the large spatial variability of droughts.

Further research examined historical drought patterns across Europe and explored the relationship between regions for developing potential drought forecasting (Hannaford *et al.,* 2011). This study was able to use the spatial coherence of drought to potentially derive an early warning system for a specific region from a drought that is developing in a different region across Europe (Hannaford *et al.,* 2011). Findings from a study by Briffa *et al. (*2009) into wet and dry summers in Europe since 1750 show that over the long-term there are prevalent trends across Europe towards much drier summers. Lloyd-Hughes and Saunders, (2002) used the Standard Precipitation Index (SPI) to produce a drought climatology for Europe 1901-1999. The results identified extreme pan European droughts during the 1940s, 1950s and 1990s, with reduced drought frequency during the 1910s, 1930s and 1980s.

Cook *et al.* (2015) constructed an "Old World Drought Atlas" (OWDA) over Europe by using instrumental records, tree-rings and documentary sources to identify mega droughts and pluvials. The OWDA also presents spatially complete data to determine the causes of Old World drought and wetness (Cook *et al.,* (2015). Results indicated that more severe, prolonged and extensive mega-droughts were experienced across Northern hemisphere land areas prior to the 20th Century. Results indicate that well below average precipitation during spring and summer 1741 may have contributed to the severity of the Irish famine 1740-1741 by impacting food production. The same study identifies some mega droughts across Europe during the 18th and 19th century. The drought events that stand out occurred during 1779-1827 with a major long duration drought from 1798 to 1808 affecting both England and Wales (Cook *et al.,* 2015).

There have been some longer-term studies into drought in the UK using precipitation observations that take advantage of a wealth of available documentary sources to assess the impacts from past droughts. Results from some of these studies found the most severe and prolonged droughts in the 19th Century were caused by a succession of dry winters, while drier summers are more prevalent in recent decades (Cole and Marsh, 2006; Marsh *et al.,*2007). Major historical drought periods have been identified in the UK during; 1854-1860, 1887/88, 1890-1910, 1921/22, 1933/34 causing widespread impacts to society (Cole and Marsh, 2006; Marsh *et al.,* 2007; Gosling *et al.,* 2012; Leonard *et al.,* 2015; Spraggs *et al.,* 2015). Historical drought research in the UK from 1891-1998 by Fowler and Kilsby (2002) found severe drought events between 1884-1896. The same research suggests that the historical drought information should be used to reassess return period estimates of contemporary drought periods (Fowler and Kilsby, 2002).

A study by Todd *et al.* (2013) into historical droughts since 1697 in the UK identified drought rich periods during 1730-1760 and 1890-2011 predominantly due to precipitation deficits. The same study suggests an increase in the occurrence of more severe droughts in the last century with the periods 1943-1950 and 1970-1978 being the most severe over the period of record 1697-2011. Some drought periods were exacerbated by increases in temperature and soil moisture deficits (Todd *et al.,* 2013). Spraggs *et al.* (2015) reconstructed droughts across the Anglian region in the (UK) from 1798 to 2010 by producing a reconstructed gridded precipitation dataset and modelling river flow. The results of the analysis identified periods of extreme drought during the 19th Century with 1854-1860 being the most severe drought across the Anglian region. Droughts during 1933-36 and 1943-1946 were most severe in the west of the region, 1889-92 more severe in the north and 1966-98 most severe across the east (Spraggs *et al.,* 2015). Results showed that the drought during 1854-1860 drought emerged as having the highest ranked severity with the period 1893-1907 also featuring strongly (Spraggs *et al.,* 2015). The study suggests that long-term precipitation, temperature and river flow data across the UK could be used to reconstruct historical drought across other regions (Spraggs *et al.,* 2015).

2.5.1 Drought analysis in Ireland

There has been limited analysis of historical droughts across the Island of Ireland. However, some studies have produced assessments of specific severe droughts. Ó Laoghóg (1979) presents results that show the east, midlands and south of Ireland were more affected by the severe drought of 1974-1976 than the west and north due to contrasting rainfall deficits. Armagh Observatory received the lowest rainfall over the period April 1975 to August 1975 since records began in 1836 (Ó Laoghóg, 1979). Phoenix Park in Dublin experienced some heavy rainfall in early May 1975 which somewhat alleviated the impacts from the drought, but rainfall for April to August 1976 was the fourth lowest since 1837. The driest period at Phoenix Park was experienced between April and August 1887 with only 125.2 mm of rain recorded, with 1870 and 1864 being other notably dry years. The same study also provides a summary of agricultural and water supply impacts caused by this period of severe drought. The period 1975-76 recorded three times the normal amount of potential and actual evapo-transpiration with soil moisture deficits most pronounced in the south east of the country. Ellison (1934) noted that the 1933 event broke all records for drought across the British Isles with rainfall totals of only 20.57 inches at Armagh. Severe drought also occurred in 1836 at Armagh with only slightly more precipitation falling than in 1933 (Ellison, 1934). Although this was a particularly dry and hot year, vegetation and crops were not adversely affected, with good harvesting in the dry September (Ellison, 1934).

Dooge (1985) briefly outlined some severe historical droughts for the period AD759-1408 taken from the Annals of Ulster and Annals of Clonmacnoise and several other historical Annals. The same study utilised other documentary sources such as Sir William Wilde's Census of 1851 tables on "Heat and Droughts" which is based on descriptive accounts and early instrumentation (Dooge, 1985). The study mentions the extremely dry years of 1887, 1927 and 1934 and reports that in 1934 the Barrow River with a catchment size of 1660 km^2 gave a runoff of only 1.1 cubic metres or equivalent to one drop per day per square metre (Dooge, 1985). In an examination of the 1976 drought in Ireland Mac Cárthaigh (1996) compared the drought of 1995. Results showed that the river flows at the end of 1976 were the lowest on record and can be used as a benchmark for future drought comparisons. However, the study also noted that during the end of the 1995 drought the river flow at some stations was the same as those measured in 1976 (Mac Cárthaigh, 1996).

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TABLE II.

Months.	Fassaroe, Bray.						Fitzwilliam Square, Dublin.*		
	Average Rainfall in inches for 30 years.	Rainfall in inches in 1887.	Excess or Deficiency 1887.	Average number of rainy days for 30 years.	Rainy days, 1887,	Excess or Deficiency, 1887.	Average Mean Temperature for 22 years.	Mean Temperature, 1887.	Excess or Deficiency.
January, ...	4.142	3.945	— .197	18.1	17	— 1.1	41.4	41.5	+ 0.1
February, ...	3.905	1.205	— 2.700	15.7	9	— 6.7	43.2	42.9	— 0.3
March, ...	3.545	2.420	— 1.125	16.2	16	— .2	43.5	41.3	— 2.2
April, ...	3.071	1.520	— 1.551	13.7	9	— 4.7	48.1	45.1	— 3.0
May, ...	2.582	1.760	— .822	14.0	13	— 1.0	52.1	51.8	— 0.3
June, ...	2.742	.285	— 2.457	13.6	4	— 9.6	57.7	62.3	+ 4.6
July, ...	2.539	1.480	— 1.059	14.6	12	— 2.6	60.7	63.7	+ 3.0
August, ...	3.046	4.230	+ 1.184	14.6	12	— 2.6	59.9	60.3	+ 0.4
September, ...	3.306	1.795	— 1.511	15.1	14	— 1.1	56.0	54.0	— 2.0
October, ...	4.705	2.640	— 2.065	18.0	10	— 8.0	50.0	47.3	— 2.7
November, ...	3.800	5.565	+ 1.765	16.3	21	+ 4.7	44.4	42.6	— 1.8
December, ...	3.948	2.530	— 1.418	16.6	19	+ 2.4	41.3	39.9	— 1.4
Total, ...	41.331	29.375	— 11.956	186.4	156	— 30.4	49.85	49.39	— .46

Ten months of deficient rainfall; two above the average rainfall.
Ten months with fewer rainy days than usual; two with rainy days above average.
Eight months colder than usual; four warmer.

* Dr. J. W. Moore, F.R. Met. Soc., 40 Fitzwilliam-square, W., has kindly furnished the records of temperature, the Fassaroe mean temperatures not having been worked out in time.

Figure 2.2 Table showing rainfall recorded at Fassaroe, Bray 1887 and presents details on monthly and annual rainfall deficits and mean temperature records taken at Fitzwilliam square Dublin. Source (Barrington, 1888).

Barrington (1888) provided a detailed drought event assessment for Ireland focusing on the severe drought of 1887. Figure 2.2 provides an example of historical climate records available in Barrington (1888) and shows the details of the precipitation and temperature during 1887 at Dublin. This study presents information on the impacts on agriculture. The drought was also illustrated by two maps which show the precipitation deficits during 1887 relative to previous years (Figure 2.3). The results showed that precipitation was below average for the whole of Ireland during 1887. Markree Observatory in the west recorded only 2% below average precipitation in 1887, however totals at Rosbercon Castle in the southeast dropped to 59% below average (Barrington, 1888). During the summer months of 1887 the most severe drought was experienced across the south and south eastern regions. During the summer months Courtown and Kilkenny located in the southeast and Cork in the south received only 30% of normal precipitation (Barrington, 1888). Barrington (1888) reports that due to the fierce heat and lack of rain most crops failed and the grass was burnt brown. This study provides crucial information which will help to improve current understanding of drought and subsequent socio-economic impacts.

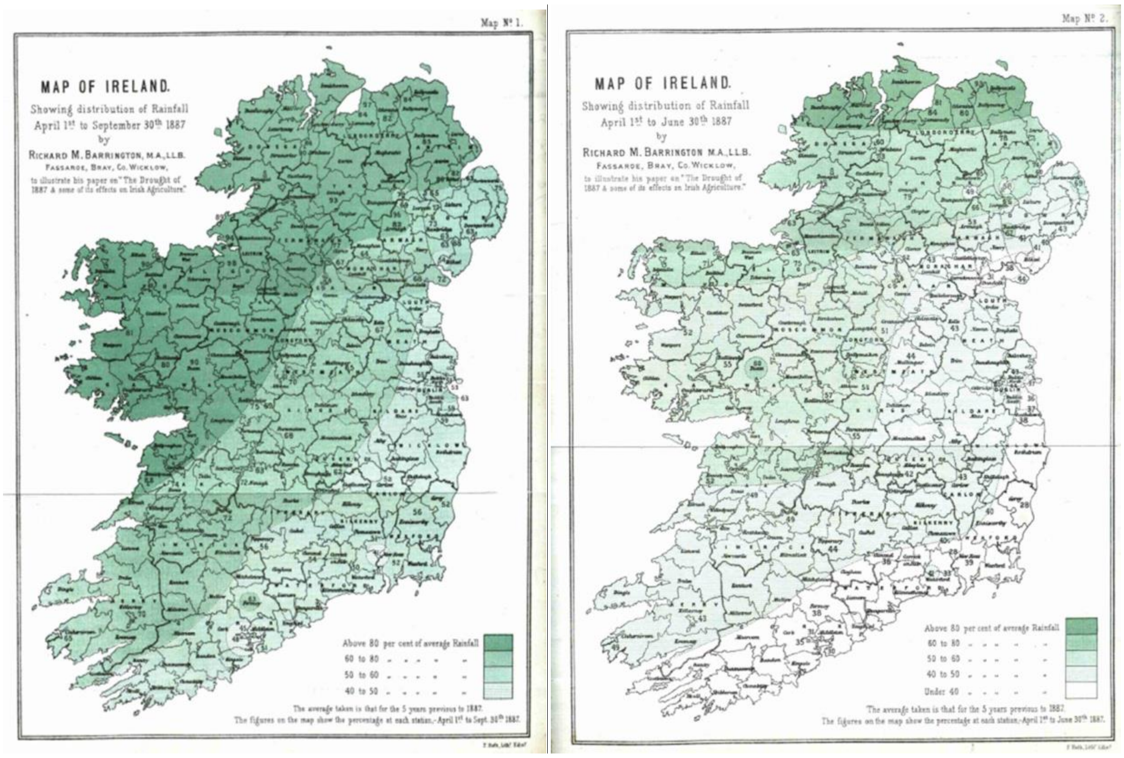


Figure 2.3 Maps produced by Barrington, (1888) showing the distribution of rainfall across the Island of Ireland April 1st to September 30th and April 1st to June 30th 1887. Source (Barrington, 1888)

2.6 Historical documentary evidence.

Many studies across Europe and the UK have integrated historical documentary evidence to reconstruct past weather and climate, validate observations and to assess the frequency and severity of extreme events (Macdonald, 2006; Brázdil *et al.*,2006; Pauling *et al.*, 2006; Pfister *et al.*, 2006; Casty *et al.*, 2007; Macdonald *et al.*, 2013; Kjeldsen *et al.*, 2014; Benito *et al.*,2015). Macdonald e*t al.*, (2014) note that integration of documentary evidence into historical hydro-climatology can considerably reduce some of the uncertainty involved in using historical observations (Macdonald e*t al.*, 2014).

Historical documentary sources in Ireland provide records of past extreme meteorological events and provide useful details of societal impacts (Ludlow, 2005). In identifying historic floods and droughts, studies have utilised documentary sources (e.g. the Annals of the Four Masters Ireland, Annals of Ulster and the Annals of Clonmacnoise) which date back to 1000 BC (Ludlow, 2006; Hickey, 2011). These monastic annals recorded extreme events throughout Ireland over varying time periods and although there are some issues with dates, duplicates and doubtful entries, they are still a very useful source for reconstructed past events (Hickey, 2011).

The British Rainfall books were first produced in 1860 by Symons as a four-page pamphlet and contained over 168 rainfall records for stations across the Irish and British Isles. The publication series continued annually until 1993 containing both interesting and invaluable information (Pedgley, 2002). Although these books mainly present monthly precipitation observations they also provide useful statistics such as number of rain-days, maximum rainfall days and long-term average comparisons (Pedgley, 2002). In addition, some of the The British Rainfall Book publications include special reports. For example, the 1887 edition presents information on historical droughts across the UK and Ireland dating back to third century (see Figure 2 4) compiled using information from various historical books and articles including the 1851 Census of Ireland.

35

barley in many places was seared before the grain was formed. W.

1825. Ireland. Extreme drought in summer and autumn. C Very parching July. W.

1826. Ireland. Remarkably hot and dry from March to June. C. Excessive drought in June. W.

1831. Great dryness from middle of July to August 31st. W. Long continued drought in Ireland checked vegetation. C.

1833. Great heat and drought all May and to June 10th. W.

1834. Sharp drought February to May, and with little intermission to July 18th. November to December also dry; water scarce. W.

1835. Very hot and dry summer. No rain in Suffolk from July 14th to August 25th; pastures burnt up, but wheat sound and abundant. W.

1836. Irish cereal crops defective from excessive drought. C.

1840. April and August very dry. W.

1842. Very hot summer, especially August, which was very dry. W.

1843. Severe drought in the first three weeks of September. W.

1844. Extraordinary drought Lady Day to Midsummer; fine wheat crop. W. Ireland. Excessive drought in spring, soil so parched that it required a pick-axe to break it. Most of the springs dried up. C.

1845. Ireland. February unusually dry, March little rain, April unusually dry, and very little rain in May. C. Drought and heat. L.D. Unusually dry Oct. 12th to Nov. 16th. W.

1846. Severe drought with heat May 21st to Sep. 23rd. One of the hottest summers on record. W.

1847. Ireland. March, July, August and September more than usually dry; green crops injured. C. July and August extremely hot and dry. W.

1849. February and March remarkably dry. W.

1850. June very dry and hot, September very dry. W.

1851. Severe drought in Suffolk at end of June. W. Ireland. Much drier than usual. C.

1857. Drought and heat. L.D.

1858. Drought and heat. L.D.

1859. Drought and heat. L.D.

1868. Drought and heat. L.D.

1869. Drought and heat. L.D.

1870. Drought and heat. L.D.

1874 Very dry summer, good harvest.

1879. Drought from October. L.D.

c 2

Figure 2.4 Example of detailed drought information compiled in Symons British Rainfall Book 1887. Source (Symons British Rainfall Book, 1887 pp 35)

In 1851 William Wilde was the sole Assistant Commissioner for the Census of 1851 and wrote two volumes referred to as the “Statistics of Disease” and the “Tables of Death” (Froggatt, 1965). These volumes contained 300 pages of analysis and detailed history of “pestilences, cosmical phenomena, epizootics and famines from the pre-historical period up to 1850 (Froggatt, 1965). Wilde also contributed to the agricultural statistics volume and along the other volumes provides a wealth of information including descriptions and timings of historical extreme meteorological events such as high temperatures, drought and flooding. Figure 2.5 presents an example of information available in the Census 1851

DROUGHTS AND HEATS, HOT SUMMERS AND MILD WINTERS.

ANALYSIS OF DROUGHTS AND MILD SEASONS.

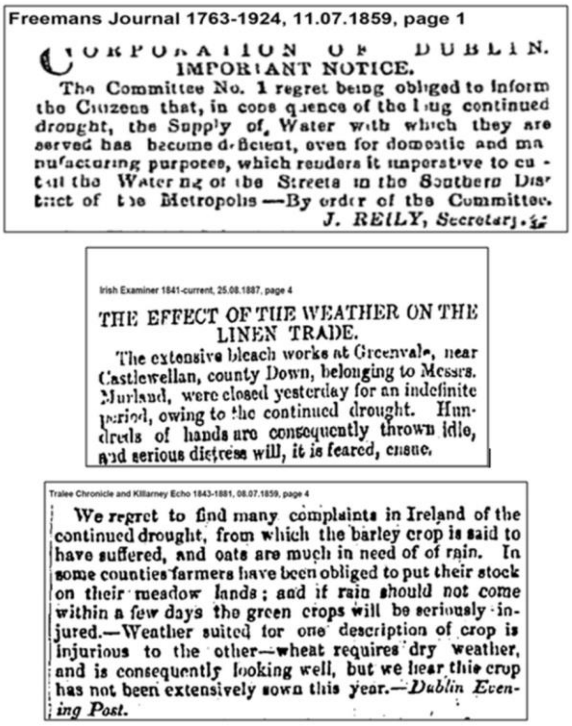
A.M. 3294. There was no rain in Ireland for ten years, notwithstanding there was abundance of grain and fruit.
A.D. 583. Intense heat in this year.
588–89. A scorching and dry summer.
592. Deficiency of heat for three years.
713. Great drought.
717. A dry summer.
720 "Was the year of Christ when the hot summer happened."
744. Great and unaccustomed drought in the world.
748. The world was parched with unusual dryness.
759. Exceeding great drought.
763–64. Drought beyond measure.
772. An unusual drought and heat of the sun.
1006. Great drought from little Christmas to May. Mild weather in this winter, so that the foliage and the wild garlic grew.
1009. A burning summer.
1076. Pestilential heat, so as to destroy very many.
1091. A year of good weather.
1129. A summer of great drought.
1252. Great heat and drought prevailed in this summer, destroying much cattle.
1262. A great drought this summer.
1263. An exceedingly hot summer.
1419. The year of the hot summer.
1471. A hot summer this year.
1492. So great a drought that many rivers were almost dried up, and much cattle died of thirst.
1539. Heat, and marvellous drought.
1575. Intense heat, and extreme drought in the summer.
1607–8. Summer very hot.
1643. Summer excessively hot in England.
1674–75. The winter unusually warm and mild.
1714–19. Six dry years here and in England.
1717. Summer hot and dry.
1718. Summer warm, fair, and pleasant Winter mild. 1719 was one of the hottest summers remembered in England.
1721. A winter mild.
1723. The summer was so remarkable for drought that salt water flowed to the quay of Limerick.
1727. Winter mild and open.
1729. Summer mostly dry.
1731. Summer hot and dry.
1733. Spring very dry; early summer dry, but concluded wet; winter so mild that primroses and violets bloomed.
A.D. 1734. Spring very warm, and winter wet and mild.
1736. One of the hottest summers that has been remembered.
1737. Some days in summer excessively hot.
1740. April. Not three hours of continued rain since the beginning of November, 1739. Summer dry. Great scarcity of water; great difficulty getting corn ground.
1741. Spring excessively dry. Summer hot; much more so than of late years.
1744. December was memorable for the great height of the barometer, and a warmth unusual to the season.
1747. Summer hot and dry. Winter mild. In England, the hottest summer since 1719.
1748. January very mild. Summer warm and dry. In Paris the thermometer rose higher than for 100 years previously.
1750. Some days in June and July the hottest in the memory of man. Horses dropped down dead.
1752. Several plants flowered a second time in September.
1758. Winter open and mild; the mildness was common to us and Russia.
1759. Winter so mild and open that many indigenous flowers blossomed in the open field.
1760. July excessively hot. Fahrenheit's thermometer stood at 78° on the 18th. In England a dry summer.
1761. Summer extraordinarily dry. The drought common to us, Italy, and Switzerland.
1762. Excessive drought, common to us, to parts of England and Europe, and to Virginia.
1764. Winter warm and moist.
1765. Extreme drought in summer. During eight years preceding this period the Fahrenheit thermometer only fell twice below the 33° of the scale.
1776. The weather so mild in December that poplar trees blossomed.
1778. Summer remarkably fine.
1780. December 19th—Continuance of thirty days of fair weather; an unparalleled phenomenon at this time of year.
1783. Summer remarkable for heat and drought.
1791. This country has not experienced so dry and warm a summer since 1733.
1800. Summer was unusually hot and dry.
1801. July—So great a degree of heat has seldom been observed in this climate.
1803. September 17—The country was

2 Y

Figure 2.5 Presents information on historical droughts and heats. The page shows information on the drought as compiled in the Census of Ireland 1851 (Census, 1851; pp 345).

The Census report of 1851 is part of the Online Historical Population reports (OHPR) which provides an online resource for Britain and Ireland for the period 1801-1937. The OHPR includes detailed textual and statistical information on the economy, society, weather, disasters, medicine, deaths and births for the 18^{th} and 19th centuries. Whistlecraft's Weather Almanac which was published annually (1856-1884) provides details on meteorological extremes across UK and Ireland. In addition, the books *Climate of England (1840)* and *Rural Gleanings (1851)* contain useful historical information on extreme events for the UK and Ireland and present subsequent socio-economic impacts and responses (Thwaites, 2015).

Changnon and Easterling (1989) used newspaper archives to understand drought impacts in two North American cities, citing newspapers as reliable indicators for the timing of impacts and adjustments as precipitation deficits develop. Mitchell (2011) highlights the potential utility of historical newspapers for supplementing evidence of past climate hazards in Ireland.



Freemans Journal 1763-1924, 11.07.1859, page 1

CORPORATION OF DUBLIN.
IMPORTANT NOTICE.

The Committee No. 1 regret being obliged to inform the Citizens that, in consequence of the long continued drought, the Supply of Water with which they are served has become deficient, even for domestic and manufacturing purposes, which renders it imperative to curtail the Watering of the Streets in the Southern District of the Metropolis.—By order of the Committee.

J. REILY, Secretary.

Irish Examiner 1841-current, 25.08.1887, page 4

THE EFFECT OF THE WEATHER ON THE LINEN TRADE.

The extensive bleach works at Greenvale, near Castlewellan, county Down, belonging to Messrs. Murland, were closed yesterday for an indefinite period, owing to the continued drought. Hundreds of hands are consequently thrown idle, and serious distress will, it is feared, ensue.

Tralee Chronicle and Killarney Echo 1843-1881, 08.07.1859, page 4

We regret to find many complaints in Ireland of the continued drought, from which the barley crop is said to have suffered, and oats are much in need of of rain. In some counties farmers have been obliged to put their stock on their meadow lands; and if rain should not come within a few days the green crops will be seriously injured.—Weather suited for one description of crop is injurious to the other—wheat requires dry weather, and is consequently looking well, but we hear this crop has not been extensively sown this year.—*Dublin Evening Post.*

Figure 2.6 Examples of excerpts from newspapers reporting on the impacts from historical extreme drought events, available from the Irish Newspaper Archive (Freeman's Journal, 11/07/1859; Irish Examiner 25/08/1887; Tralee Chronicle and Killarney Echo 04/07/1859) downloaded from Irish Newspaper Archive: http://archive.irishnewsarchive.com/

The Irish Newspaper Archive is an online resource of over 50 different Irish historical regional and national newspapers. The archive contains newspaper articles dating from the early 1700's to current times, including the Belfast Newsletter (1738-1890), Freeman's Journal (1763-1924) and The Leinster Express (1831-current). The Belfast Newsletter is one of the world's oldest continuously published English language daily newspapers and provides important insights into Ireland's past (Mitchell, 2011). The online database allows for searches to be conducted using specific key words such as (drought, floods, or rainfall) over periods of interest to retrieve the exact published format (See examples in Figure 2.6).

2.7 Gaps in the knowledge and justification for this research.

Previous research using long term rainfall records across the UK and Europe have provided critical information on the past climate. These studies have highlighted variability and change while contextualising recent extreme climatic events such as prolonged dry and wet periods. The evidence suggests that the hydrology of Europe and the UK has seen considerable changes over the past two centuries. Most studies in Ireland have been restricted to short records, but there is a clear opportunity to utilise the hard copy long-term precipitation records in Met Éireann to supplement the existing long-term precipitation catalogue.

Ireland is a sentinel location situated along the Atlantic fringe and it is crucial that long-term records are utilised allowing for more robust assessments, to help understand what changes have occurred over the past centuries. The historical documentary resources available in Ireland outlined in this chapter can be combined with historical observations.

The literature review presented above has identified the following research gaps:

Research Gap 1: Due to a paucity of good quality long-term precipitation records there is a clear necessity and opportunity to rescue and digitise data from the archived records in Met Éireann. This will expand and extend the existing long-term monthly precipitation records and allow for more robust quality assurance and data homogenisation. Thesis **objectives (1 and 2)** will be addressed in Chapter 3

Research Gap 2**:** Previous research across Europe and the UK has shown the importance of long records in detecting trends and identifying variability and change while contextualising recent extremes. There is a considerable gap in knowledge concerning long-term changes in Irish precipitation due to the lack of quality assured long-term records. Thesis **objective 3** will also be dealt with in Chapter 3

Research Gap 3: There has been no detailed assessment of historical drought for the Island of Ireland. Details on droughts prior to the 1940s would provide crucial information for water resource management. This forms **objective 4** and will be addressed in Chapter 4

Research Gap 4: There is a significant knowledge gap in our understanding of long-term variability and change in river flows, again due to the lack of long-term flow records in Ireland. Most studies have been forced to conduct analysis over short periods, which can present misleading results. Addressing research gap 1 would provide an opportunity to reconstruct long-term Irish river flows for selected catchments. Thesis **objective 5** will be dealt with in Chapter 5

2.8 Research objectives

Addressing the above research gaps this thesis has the following objectives:

Thesis objective 1: To expand and extend the existing long-term monthly precipitation catalogue for Ireland by digitising hard copy archived monthly precipitation and to compile detailed metadata and station history from all available sources.

Thesis objective 2: Meticulously check the precipitation records for homogeneity using state of the art methods.

Thesis objective 3: Conduct a comprehensive analysis of how precipitation has changed in Ireland at the longer time scale.

Thesis Objective 4: To produce a detailed historical drought catalogue for Ireland and to integrate qualitative historical documentary evidence to validate and add further confidence to the quantitative assessment.

Thesis objective 5: Use the long precipitation records to reconstruct long-term monthly river flow records at selected Irish catchments and identify historical hydrological drought

The next chapter deals with thesis **objective 1** in supplementing the existing long-term precipitation records using digitised rescued hard copy precipitation records held in Met Éireann's archives. The same chapter will address **objective 2** to employ HOMER homogenisation software to quality assure and check the new Irish long term precipitation series for homogeneity. The homogenous records will be analysed for variability and change. Additionally, to address **objective 3** annual and seasonal precipitation will be assessed to identify emerging trends.

3 Homogenisation and analysis of an expanded long-term monthly rainfall network for the Island of Ireland (1850-2010)

3.1 Introduction

Long precipitation series help contextualise recent climate variability, identify emerging trends, ground-truth climate model projections and understand impacts on sectors such as agriculture, water resources and flood management (e.g. Jones *et al.*, 2006; Wilby and Quinn, 2013). High-quality observations prior to 1900 are relatively rare (Jones, 1984; Burt *et al.*, 1998; Barker *et al.*, 2004; De Jongh *et al*., 2006; Jones *et al*., 2006; Wilby, 2006; Burt *et al.*, 2014). However, several European studies have employed long-term precipitation records to detect change and contextualise shorter series (Auer *et al*., 2005; De Jongh *et al*., 2006; Moberg *et al*., 2006).

The pioneering work of Tabony (1980) is of particular significance to the British-Irish Isles (BI). This composite of long-term monthly rainfall records was based on 185 sites across Europe with data collated from various National Meteorological Services (Tabony, 1980). Long-term precipitation series were then constructed using combinations of overlapping records adjusted by correction factors to produce continuous series. Briffa (1984) also produced long-term composite rainfall records including four sites in Ireland using methods similar to Tabony (1980). Others have subsequently updated the work of Tabony (1980) and Briffa (1984) (e.g. Jones, 1983; Gregory *et al.*, 1991; Jones and Conway, 1997; and Burt *et al.*, 2014). Additional long-term regional rainfall reconstructions include the work of Barker *et al*. (2004) who constructed a 200-year monthly precipitation series for the English Lake District through bridging between non-continuous station records, and Todd *et al.* (2014) who produced an extension of composite rainfall series for Carlisle (northwest England) to homogenise station records back to 1757.

Analysis of these records has yielded important insights. For example, Burt *et al.* (1998) used precipitation records from 1880-1997 to show that the most notable period of drought occurred in 1991 together with changes in the seasonality of rainfall (winter/summer contrast becoming more extreme in decades prior to 1997). More recently, Burt *et al.* (2014) employed long-term precipitation records for the BI to analyse and contextualise very high monthly rainfall totals in the 1870s relative to recent rainfall extremes.

In Ireland, most precipitation analyses have been restricted to relatively short records (post 1940s) due to a lack of suitably quality controlled or homogenised long-term datasets (e.g. Kiely, 1999; Sheridan, 2001; Wang *et al.*, 2006; Leahy and Kiely, 2011; Dwyer, 2012). A few studies have taken a longer-term view; McElwain and Sweeney (2007) assessed monthly data at Birr and Malin Head from 1890-2003 and found significant increases in annual totals at Malin Head with no trends present at Birr (McElwain and Sweeney, 2007). Jones and Conway (1997) calculated area average monthly precipitation for the whole of Ireland for the period 1840-1995 using station observations and reconstructions from tree rings. They found that all regions have seen increases in winter precipitation and decreases in summer over the period. Butler *et al.* (1998) used records for Armagh observatory, Northern Ireland, dating back to 1838 to show summers have become drier since the 1960s.

A homogeneous climate time series is defined as one where variability is only caused by changes in weather or climate (Freitas *et al*., 2013). Most decade to century-scale time series of atmospheric data have been adversely impacted by inhomogeneity caused by, for example, changes in instrumentation or observer practices, station moves, or changes in the local environment (e.g. urbanisation). Some of these factors can cause abrupt shifts; others gradual changes over time, which can hamper identification of genuine climatic variations or lead to erroneous interpretations (Peterson *et al*., 1998).

Homogeneity tests can be broadly divided into “absolute” and “relative” methods. The former are applied to individual candidate stations to identify statistically significant breaks in data while relative methods entail comparison of correlated neighbouring stations with a candidate station to test for homogeneity. Reference series, which have ideally experienced all of the broad climatic influences of the candidate but no artificial biases, are commonly used to detect inhomogeneity in relative methods (WMO, 2011), as well as to assess the quality of the homogenisation process (Kuglitsch *et al.*, 2009). Reference series themselves do not need to be homogeneous (Szentimrey, 1999; Zhang *et al.*, 2001; Caussinus and Mestre, 2004), but must encompass the same climatic signal as the candidate (Della-Marta and Wanner, 2006). Relative homogenisation is more robust than absolute methods provided station records are sufficiently correlated (Wijngaard *et al.,* 2003). However, relative approaches can be confounded by lack of long records at neighbouring stations for comparison, and by simultaneous changes in measuring techniques across a network (Peterson *et al.,* 1998; Wijngaard *et al.,* 2003).

All homogeneity approaches benefit from reliable metadata and station histories to account for breaks and potential outliers. Metadata can provide information such as location of station instruments, when and how observations were recorded, notes on instrument changes and malfunctions or any environmental changes (such as vegetation encroachment at the site). This information is critical in interpreting statistical homogeneity tests and for informing the nature and magnitude of adjustments that might be applied to data.

New techniques are emerging for the detection and adjustment of inhomogeneity in climate series (Cao and Wan 2012; Toreti *et al.,* 2012; Freitas *et al.,* 2013; Mestre *et al.,* 2013) and the correction of multiple change points using reference series (Peterson *et al.,* 1998; Menne and Williams, 2005; Toreti *et al.,* 2012). A comprehensive assessment of homogenisation techniques for climate series was included in the scientific programme of the COST Action HOME ES 0601 *Advances in Homogenisation Methods of Climate series: An integrated approach*. The HOME objective was to develop a standardised homogenisation method for homogenising climate and environmental datasets. This led to the release of two new software packages: i) HOMER for the homogenisation of monthly data; and ii) HOM/SPLIDHOM for daily data homogenisation (HOME, 2013).

This chapter aims to construct a temporally homogenised, long-term Island of Ireland Precipitation (IIP) archive by drawing on the tools of the HOME Cost Action and seminal works of Tabony (1980), Briffa (1984) and Burt and Jones (2014). The objectives are four-fold. First, this research expands the existing catalogue of long-term monthly rainfall stations available in Ireland by recovering data for an additional eight stations. Where valuable but discontinuous records are available this study reconstructed composite series. Second, this thesis homogenised the expanded catalogue of 25 stations using the software and approach of the HOME COST action. Third, this research uses the expanded network to extend and update all stations to a common period of 1850-2010. Fourth, this research assesses variability and change within this expanded, extended and quality assured network. The remainder of the paper is organised as follows: section 2 describes the datasets and methods used for data updating and preparation, steps involved in homogenising the network and the techniques used to analyse variability and change. Results are presented in section 3 with the main findings discussed in section 4. Final conclusions and opportunities for further research are set out in section 5.

3.2 Data and Methods

Data analysis was executed in three stages: i) preparation; ii) homogenisation; and iii) analysis of variability and change across the homogeneous IIP network. Figure 3.1 illustrates the key steps involved in each stage with the following sections elaborating the datasets and methods used.

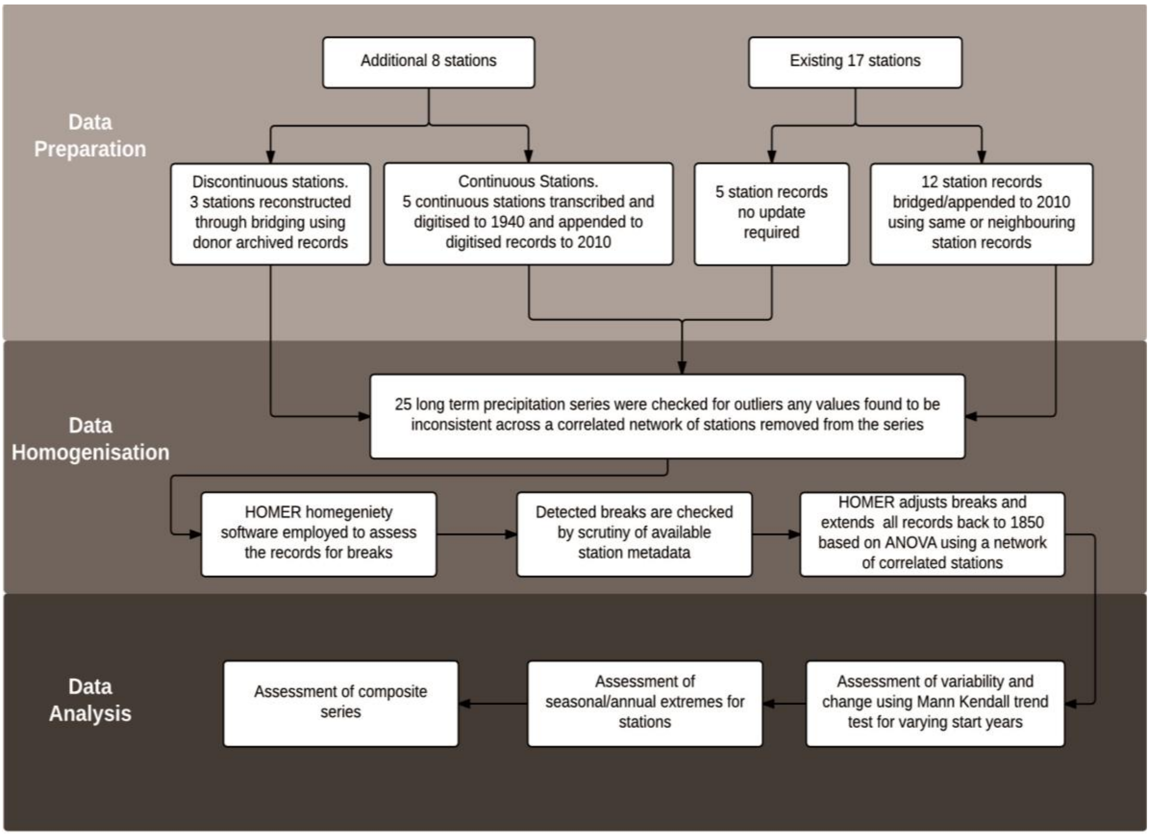


Figure 3.1 Workflow stages and key steps in data preparation, homogenisation and analysis.

3.2.1 Data Preparation

Existing long-term monthly precipitation records for the Island of Ireland (IoI) were obtained from the Climatic Research Unit (CRU). This dataset contains monthly data for 17 stations with variable start and end dates. All stations in this archive were updated to a common endpoint of 2010 using digitised precipitation records for the period 1941-2010. For Ireland post 1940 data were obtained from Met Éireann while for Northern Ireland station data was acquired from the Centre for Environmental Data Archival (CEDA) at the British Atmospheric Data Centre (BADC). Five stations in the CRU archive required no updating and were employed as downloaded. For a further two sites, data for the same station were available. Following checks for consistency using an overlapping period, these series were updated. For the remaining ten stations, records were discontinuous due to station closures or moves and updating was implemented by bridging to local stations.

Following Barker *et al.* (2004) and Todd *et al.* (2014) seasonal regression analysis was used to bridge station records. In each case, seasonal mean precipitation series were derived for available data, then regression equations calculated for overlapping periods for final adjustment of donor records to match the primary station. Note the term 'donor stations' is used to refer to neighbouring stations with overlapping records. An additional eight stations were recovered from the archives. Data was obtained from two sources at Met Éireann: i) archived precipitation records collected prior to 1941 and held in paper form; and ii) digitised records for selected stations (post 1940).

Available hard-copy records were scrutinised for stations suitable for transcribing based on criteria including: record length, fraction of missing data, availability of post 1941 digitised data, and geographical location. These procedures short-listed five records (Portlaw, Foulkesmills, Drumnsa, Galway and Mullingar) that comprise mainly continuous records from the 19th century to present. Following checks for consistency with overlapping periods, data for these stations were simply appended to the start of existing digitised station records for the period 1941-2010.

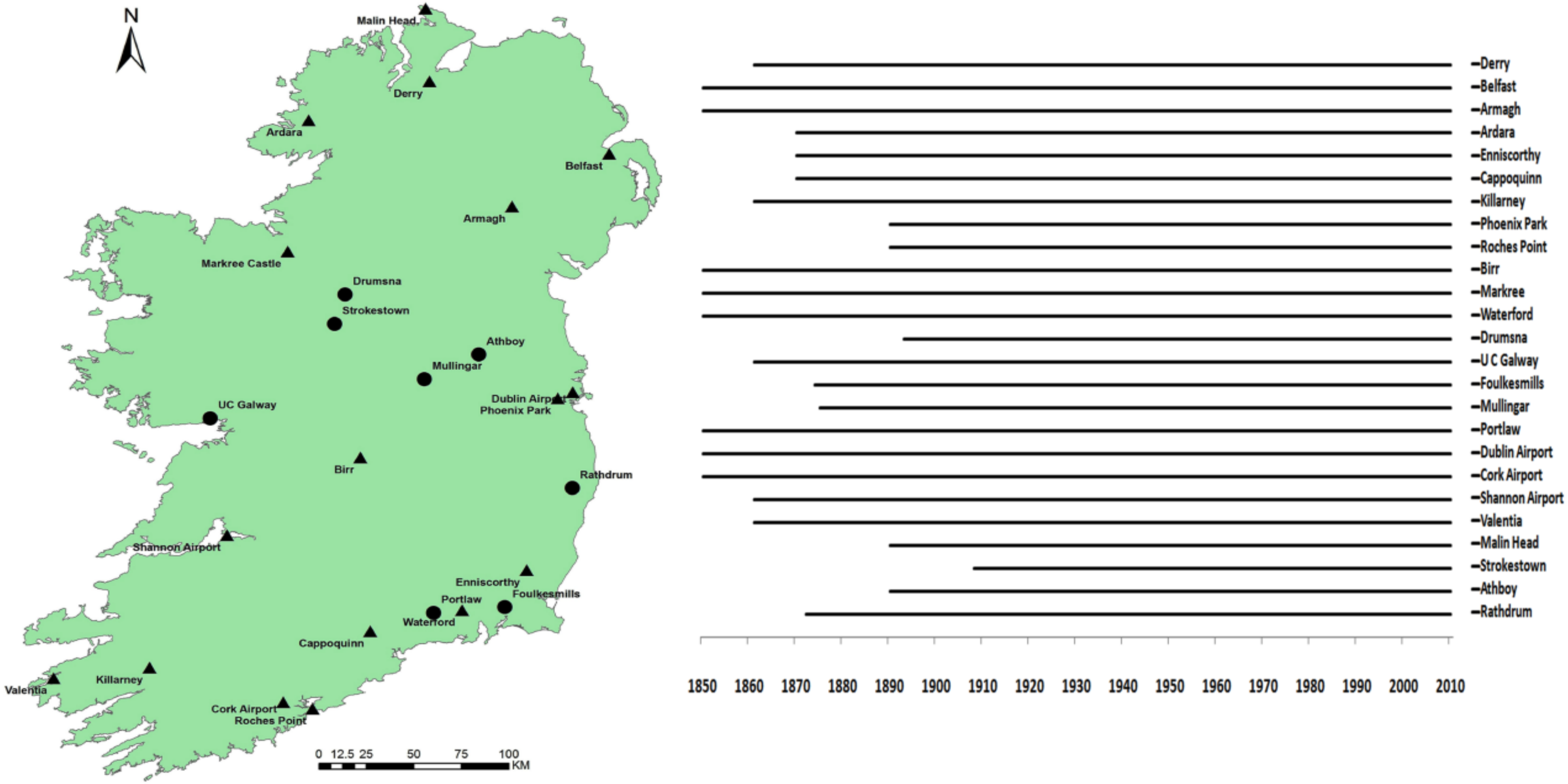


Figure 3.2 Location and updated records length (before extension to common start of 1850) for 25 stations used in analysis. Triangles represent the existing 17 archive stations; circles represent the additional eight stations added in this analysis.

A further three discontinuous archived stations (Rathdrum, Strokestown and Athboy) were also identified. Rather than lose the valuable information available for these stations, bridging and infilling from donor stations (using seasonal regression) was undertaken to develop continuous series. For these three stations suitable archived donor stations were also transcribed and digitised to extend primary station records back in time. For the period following primary station closure, composite monthly series from operational local stations were calculated for years up to 2010. Figure 3.2 maps the location of all 25 stations used in the analysis and shows record length for all stations following updating to 2010. Figure 3.3 provides details on the primary and donor archived stations selected for transcribing and overlapping periods.

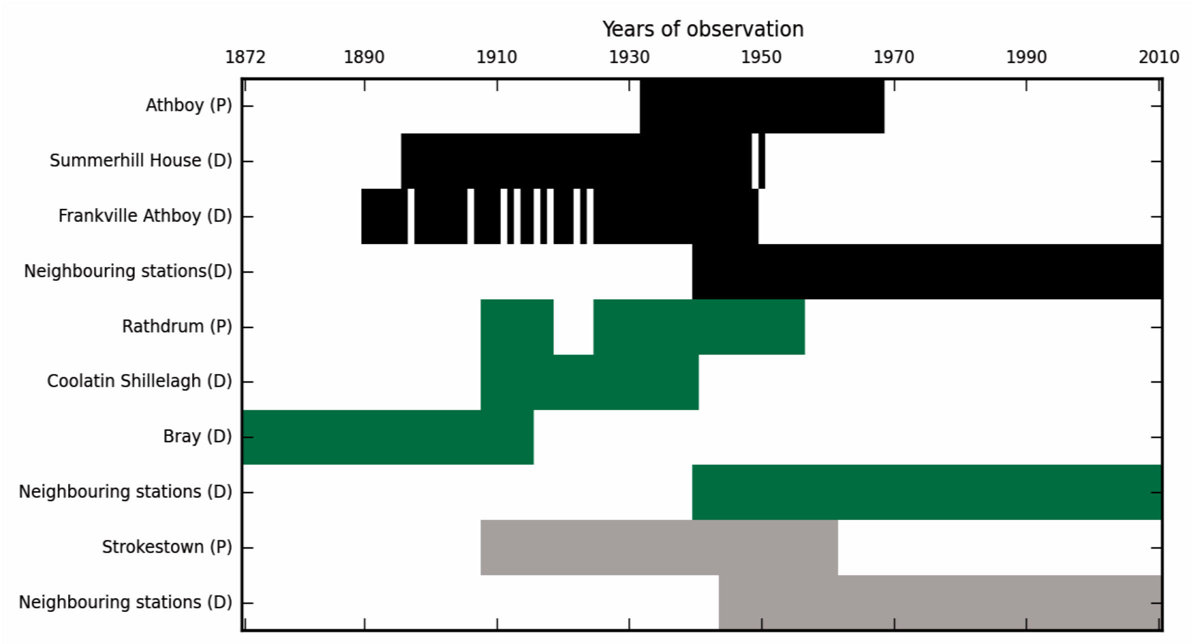


Figure 3.3 Primary stations (P) Athboy (black), Rathdrum (dark grey) and Strokestown (grey) and overlapping records for donor stations (D) used for bridging and infilling.

3.2.2 Bridging of discontinuous stations

Bridging was required for three of the new series and ten stations in the CRU archive because of station closures/moves. Bridging was undertaken using seasonal regression on overlapping records to derive adjustment factors. For each station, details on derived regressions and adjustment factors are given in Table 1.1. All regression models were significant at the 0.05 level. For these stations appropriate bridging stations could be found in close proximity. The poorest regressions were derived for Roches Point, Derry, Belfast and Ardara where a lack of suitable local bridging stations meant candidates were derived from further afield. However, with the exception of Enniscorthy, all seasonally derived correction factors are <10% but typically much lower (Table 3.1).

For the three discontinuous series the majority of bridging steps result in seasonally derived adjustments that are typically within ±5% (Table 3.1). For Rathdrum and Athboy, bridging with Shillelagh and Frankville House respectively show larger adjustments (Shillelagh winter and spring; Frankville House all seasons). For Rathdrum, available records were transcribed from 1908-1958 and extended to 1875-2010. Records at Shillelagh were seasonally adjusted and used to infill missing records at the primary station for the period 1919-1925 using seasonal regressions derived for the overlapping period 1909-1940 (R^2 > 0.66 for all seasons). Longer records available for Bray were next used to extend the record to 1875 using seasonal adjustments developed for the overlapping period 1908-1915 (R^2 0.67 in spring; 0.98 in winter). Finally, the extended series was updated to 2010 by bridging to the composite series from local records through seasonal adjustments developed over the period 1941-1958 (R^2 > 0.90 in all seasons).

At Athboy transcribed records cover the period 1932-1968. Bridging facilitated reconstruction of the series from 1890-2010. Data from Summerhill House was used to extend the record to 1896 using seasonal adjustments developed from the overlapping period 1932-1950 (R^2 ranging from 0.72 in winter to 0.85 in autumn). Records for Frankville House were then used to extend adjusted series back to 1890 using adjustment factors developed for the overlapping period 1896-1940. Composite series derived from local stations were used to update the record to 2010 based on seasonal adjustments derived from the period 1941-1968 (R^2 ranges from 0.90 in summer to 0.94 in spring and autumn). Finally, for Strokestown hard copy records were transcribed from 1908 to station closure in 1961. A composite of local stations were used to update the record to 2010 based on seasonal adjustment factors derived from the overlapping period 1944-1968. Seasonal regressions for this site had R^2 values of 0.95 in winter and summer and 0.98 in spring and autumn.

Primary station	Donor Station(s)	Overlapping	Winter	Spring	Summer	Autumn
520 Rathdrum 1908-1958	Bray	1908-1915 N=8	R^2= 0.983 CF x 1.014 MAE -0.65	R^2 = 0.865 CF 0.990 MAE 0.15	R^2 = 0.983 CF x 0.986 MAE -0.57	R^2 = 0.678 CF x 0.979 MAE 0.10
	Shillelagh	1909-1940 N=25	R^2= 0.665 CF x 0.855 MAE 2.82	R^2 = 0.689 CF x0.877 MAE 1.16	R^2 = 0.676 CF x 0.992 MAE 0.39	R^2 = 0.799 CF x 0.955 MAE -1.36
	624, 1024, 1124 Roundwood	1943-1958 N=16	R^2 =0.945 CF x 0.986 MAE -0.84	R^2 =0.928 CF 0.948 MAE 1.48	R^2 = 0.868 CF x 1.00 MAE 0.32	R^2 = .949 CF x 0.945 MAE -1.00
1031 Athboy 1932-1968	231 Frankville House	1896-1940 N= 33	R^2 = 0.775 CF x 1.188 MAE 0.28	R^2 = 0.826 CF x 1.125 MAE 0.21	R^2 = 0.779 CF x 1.094 MAE 0.66	R^2 =0 .832 CF x 1.177 MAE -0.29
	Summerhill House	1932-1950 N=18	R^2 = 0.719 CF x 0.951 MAE 0.15	R^2 = 0.822 CFx0.971 MAE 1.14	R^2 =0 .723 CF x 0.968 MAE 0.68	R^2 =0 .852 CF x 0.957 MAE 0.31
	2931 Warrenstown; 1731 Ballivor GS; 431 Dunsany Castle; 931 Kells; 2531 Navan; 2531 Navan	1941-1968 N=27	R^2 =0 .921 CF x 0.993 MAE 0.08	R^2 = .9359 CF x 0.992 MAE 0.28	R^2 =0 .8962 CF x 0.971 MAE 0.40	R^2 =0 .942 CF x 1.041 MAE 0.04
229 Strokestown 1908-1961	Strokestown GS; Tulsk GS; Elphin, Dromod, Drumsna	1941-1961 N=18	R^2 = 0.951 CF x 0.956 MAE -0.03	R^2 = 0.976 CF x0.957 MAE 0.02	R^2 =0 .952 CF x 0.938 MAE 0.18	R^2 = 0.978 CF x 0.952 MAE 0.49
119 Birr 1845-2000	Birr	1958-2000 N=53	R^2 = 0.996 CF x 0.999 MAE 0.29	R^2 = 0.997 CF x 1.00 MAE 0.58	R^2 =0 .994 CF x 0.9936 MAE -0.43	R^2 = 0.997 CF x 0.997 MAE 0.07
841 Ardara 1870-1994	441 Glenties	1941-1994 N=55	R^2 = 0.73 CF x 0.94 MAE 2.54	R^2 = 0.86 CF x 0.93 MAE 4.72	R^2 =0 .63 CF x 0.911 MAE 6.93	R^2 = 0.83 CF x 0.94 MAE 5.27
Belfast 1819-1976	Hillsborough	1961-1976 N=16	R^2 = 0.80 CF x 0.83 MAE 0.53	R^2 = 0.82 CF x 0.85 MAE 0.78	R^2 =0.88 CF x 0.81 MAE 0.70	R^2 = 0.84 CF x 0.85 MAE 4.92
3106 Cappoquinn 1870-1994	1106 Cappoquinn	1945-1994 N=49	R^2 = 0.97 CF x 1.00 MAE 1.23	R^2 = 0.98 CF x 0.99 MAE 0.54	R^2 =0.98 CF x 0.99 MAE 0.89	R^2 = 0.95 CF x0.98 MAE 1.28
Derry 1861-1976	Coleraine Cutts	1961-1976 N=16	R^2 = 0.92 CF x 0.98 MAE 1.23	R^2 = 0.66 CF x 0.99 MAE 0.54	R^2 =0.39 CF x 0.96 MAE 0.89	R^2 = 0.86 CF x0.99 MAE 1.28
2715 Enniscorthy 1870-1994	4015 Enniscorthy Brownswood	1966-1994 N=29	R^2 = 0.92 CF x 0.74 MAE -0.02	R^2 = 0.85 CF x 0.75 MAE 2.41	R^2 =0.79 CF x 0.83 MAE 1.64	R^2 = 0.89 CF x 0.83 MAE 1.07
3205 Killarney 1861-1994	3205 Killarney	1969-1994 N=26	R^2 = 0.74 CF x 1.19 MAE 9.21	R^2 =0.93 CF x 0.93 MAE 4.54	R^2 = 0.78 CF x 1.10 MAE 3.07	R^2 = 0.81 CF x 1.13 MAE 7.53
636 Markree 1833-1995	Markree	1940-1995 N=56	R^2 = 0.94 CF x 1.01 MAE 0.82	R^2 = 0.96 CF x 1.01 MAE 2.04	R^2 =0.97 CF x1.01 MAE 2.60	R^2 = 0.96 CF x 1.02 MAE 2.40
Roches Point 1890-1990	Cork	1890-1990 N=101	R^2 =0 .70 CF x 1.14 MAE 4.02	R^2 = 0.67 CF x 1.07 MAE 2.78	R^2 =0.63 CF x 0.97 MAE 5.15	R^2 = 0.68 CF x 1.07 MAE 33.61
112 Waterford 1843-1994	7412 Waterford Adamstown	1966-1994 N=28	R^2 = 0.80 CF x 1.03 MAE 0.18	R^2 = 0.95 CF x 1.09 MAE 3.17	R^2 =0.61 CF x 1.01 MAE 2.23	R^2 = 0.57 CF x 1.01 MAE 11.47

Table 3.1 Bridging metrics for 13 stations (3 archived stations followed by 10 CRU stations). Details of the donor station(s) are provided together with overlapping years on which seasonal regression models were derived. The quality of the bridging is shown by the amount of explained variance (R2), Mean Absolute Error (MAE) and derived seasonal Correction Factor (CF). All regression models are significant (p<0.05).

Metadata and methodological information were gathered for the CRU series (Jones, *pers. comm.*). When transcribing and digitising the eight new stations careful note was made of available metadata and station notes on hardcopy records for both primary and donor stations. Other metadata and station notes were derived from Met Éireann and Armagh Observatory. All metadata collected are documented in detail in Appendix 1. This information was used to check breaks detected by the homogenisation process described below.

3.2.3 Data Homogenisation

The HOMER (HOMogenisation softwarE in R) package was a key deliverable of the COST action HOME and represents a synthesis of homogenisation approaches (Mestre *et al.*, 2013), including PRODIGE (Caussinus and Mestre, 2004), ACMANT (Domonkos, 2011; Domonkos *et al.,* 2011) and CLIMATOL (Guijarro, 2011). HOMER is an interactive semi-automatic method for homogenisation where the user can take advantage of available metadata in the detection and correction of time series (Vertacnik *et al*., 2015). HOMER was deployed to detect and correct inhomogeneity in the 25 monthly IIP series and to extend all records to a common period 1850-2010.

HOMER detects change points (or breaks) using dynamic programming (Hawkins, 2001), penalized likelihood criteria pairwise comparisons, and joint segmentation (Picard *et al.*, 2011). This study deployed pairwise comparisons as adopted by PRODIGE. This algorithm implements optimal segmentation with dynamic programming, an information theory based formula for determining the number of segments in time series (Caussinus and Lyazhri, 1997), and a network-wide unified correction model based on a two factor ANOVA model (Caussinus and Mestre, 2004; Mestre *et al*., 2013; Mamara *et al*., 2014).

In pairwise testing, reference series are treated as sections of the time series between two change points. Reference series are compared with all others from the same climate region to produce series of differences between the candidate and others in a defined network. Difference series are then tested for change points (Mamara *et al.*, 2014). Once detected breaks have been checked against metadata, non-homogenous series are corrected using an ANOVA model (for a full technical description see: Mestre *et al.* 2013 and Mamara *et al.* 2014).

Creation of a reference network for a given candidate station is a key step in the homogenisation process. The network can be defined based on geographic proximity or station correlation. To ensure that candidate stations have sufficient reference stations for each year of the series, it is necessary to set the minimum number of reference stations (Vertacnik *et al.,* 2015). Rather than use geographic distance options for a relatively sparse network, first difference correlations were used to identify 12 reference stations for each candidate station as recommended in the literature (Alexandersson and Moberg, 1997; Peterson *et al.*, 1998; Štěpánek and Mikulová, 2008; Coll *et al*., 2014). Further, the selection of 12 neighbours facilitated the homogenisation and extension of all series to a common period of 1850-2010 while avoiding a known limitation of the software to correct when there are many blocks of missing contiguous data distributed across candidate and/or reference series (Coll *et al*., 2015).

A three-stage application of HOMER was adopted to allow greater scrutiny of detected inhomogeneity before corrections were applied. First, basic quality control and network analysis were performed. Outliers were identified using both HOMER and visual inspection by defining minimum and maximum monthly outliers as values exceeding ±1.96 standard deviations from the respective series mean. The initial identified outliers were checked against correlated reference stations as well as metadata. The erroneous values were easily identified as in most cases they were not comparable with correlated stations and considerably exceeded the ±1.96 standard deviations threshold. Once identified the likely cases were removed from the series.

Second, HOMER was run to identify breaks within each time series. Detected breaks were not corrected automatically; all were checked for consistency with correlated reference stations and by scrutiny of metadata. Third, following confirmation of breaks with available metadata HOMER was used to correct series for inhomogeneity and missing values. Following the recommendations of Venema *et al*. (2012) annual corrections were applied in PRODIGE with multiplicative corrections applied using the amplitude of detected breaks. Therefore, for a break amplitude of e.g. + 0.15, the data before the detected break is multiplied by 1.15 (increase in mean of 15%). As a final step HOMER is used to infill missing data for all series to 1850. PRODIGE allows correction of the missing data using adjustment based on break amplitude with adjustment applied until the first detected change point of the series.

3.2.4 Quality Assuring Homogenised Series

Following application of HOMER quality assurance of homogenised series was undertaken in three ways. First this study examined sensitivity of break detection to network density. Previous experience recommends that at least 50% shared variance (r^2) is needed between candidate and reference series (Scheifinger *et al.,* 2003; Auer *et al*., 2005). At lower levels, detection of discontinuities can be hampered by statistical noise. Scarcity of long records means that station density is relatively low across the island, yet extension to a common period required selection of 12 reference stations for each candidate to avoid issues of excessive missing data. Both of these objectives have the potential to lessen the availability of sufficiently correlated reference stations. Thus, the sensitivity of break detection to network density was explored by re-running HOMER for all stations over the period 1941-2010 using a finer network of 211 digitised precipitation stations. Break detection frequency and consistency of timing of breaks in the period 1941-2010 using both networks was examined.

Second, the Pettitt (1979) statistic was used to examine the HOMER homogenised annual IIP station series for any remaining change points. The Pettitt test is an absolute, nonparametric test for detecting change points, and is relatively insensitive to outliers and skewed data (Pettitt, 1979). The null hypothesis (no change point in time series) against the alternative (an upward or downward change point in a given year) was tested at the 0.05 level. Finally, this research constructed an Island of Ireland precipitation (IIP) series derived as the unweighted average across all stations for the period 1850-2010, both to assess variability and change at the island level but also for comparison with overlapping periods in other long running climatological series, including; the England and Wales Precipitation (EWP) series (Alexander and Jones, 2001) and storminess indices for the British-Irish Isles (Matthews *et al*., 2015). Spearman's rank correlations were also derived between seasonal and annual IIP series and the North Atlantic Oscillation Index (NAOI) (accessed http://www.cru.uea.ac.uk/cru/data/nao/).

3.2.5 Analysing variability and change

Variability and change was assessed for all 25 homogenised stations in the IIP network together with the IIP series. For each station 11-year moving averages for annual and seasonal (winter (DJF), and summer (JJA)) series were computed. Driest/wettest years were identified annually and seasonally at all 25 stations and the IIP series, with the latter compared to EWP. The non-parametric Mann-Kendall (MK) test (Kendall, 1975) was used to detect monotonic trends in seasonal and annual mean series for each IIP station and the IIP series. The MK test statistic (Zs) has mean of zero and variance of one. Positive (negative) Zs indicates a positive (negative) trend in precipitation. The magnitude of Zs indicates strength of the trend. Trend significance was assessed at the 0.05 level using a two-tailed test. The null hypothesis, H_0, of no trend (positive or negative) was rejected if MK $|Zs| > 1.96$. Homogenised series were also checked for lag one serial correlation (no lag one autocorrelation detected 0.05 level). Following Wilby (2006) and Murphy *et al.* (2013) dependency of trends on the period of record was investigated by varying the start year of the analysis to explore trend development over time. The MK Zs statistic was first calculated over the full record, i.e. 1850-2010, then 1851-2010 and so on, to a minimum record length of 30 years. Finally, trends in seasonal means for the IIP series were assessed using a moving windows approach for all possible start and end dates with a minimum record length of 10 years.

3.3 Results and Chapter Discussion

3.3.1 Homogenisation and extension to 1850

Following updating and bridging procedures record lengths across the 25 IIP stations range between 101 and 161 years with mean 139.6 years. HOMER identified 12 reference stations within the network for each candidate station for pairwise comparison and joint detection of possible breaks. Table 3.2 provides the mean correlation coefficients (*r*) along with the range of *r* for each station and corresponding reference network.

Mean *r*-values for all pairs of candidate and reference series ranged between 0.58 (Malin Head) to 0.80 (Foulkesmills). Outlier detection revealed 53 inconsistent monthly values across 16 stations. The station at the University College Galway (UCG) accounted for 30% of outliers and Valentia for 16%, with the remainder spread across the other 14 stations. HOMER was first run on all series with known outliers included, and the results scrutinised; series were then re-processed in HOMER following the removal of outliers. However, the distribution of years with breaks detected by HOMER remained the same, indicating that for this network break detection by the programme is not sensitive to outliers.

Station name	**Mean *r***	**Range of *r***
Armagh	0.76	0.70 - 0.82
Roches Point	0.75	0.63 - 0.91
Athboy	0.78	0.72 - 0.87
Foulkesmills	0.80	0.69 – 0.92
Waterford	0.78	0.66 – 0.92
Birr Castle	0.76	0.70 – 0.87
Mullingar	0.79	0.72 - 0.88
Drumsna	0.75	0.66 – 0.89
Portlaw	0.78	0.67 – 0.89
Phoenix Park	0.73	0.64 – 0.98
Belfast	0.72	0.66 – 0.82
Enniscorthy	0.79	0.69 – 0.91
erry	0.70	0.58 - 0.80
Valentia	0.71	0.64 – 0.83
Cappoquin	0.79	0.73 – 0.88
Killarney	0.71	0.67 - 0.83
Cork Airport	0.75	0.62 - 0.91
UC Galway	0.67	0.57 - 0.78
Strokestown	0.79	0.73 – 0.89
Shannon Airport	0.71	0.62 – 0.81
Rathdrum	0.78	0.70 – 0.86
Dublin Airport	0.74	0.64 – 0.98
Malin Head	0.58	0.43 – 0.75
Markree Castle	0.75	0.62 – 0.83
Ardara	0.69	0.58 – 0.80

Table 3.2 Mean and range of first difference correlation coefficients for the identified reference station networks for each of the 25 candidate stations.

Eleven stations were found to be homogenous, but 25 breaks were detected by HOMER across the other 14 stations. Multiple breaks were found in 7 records: six in the UCG series; two for Malin Head, Belfast, Mullingar, Drumsna, Portlaw and Roches Point; and a single break point in each of the remaining seven series. Metadata scrutiny revealed that 20 of the breaks detected are coincident with issues such as changes in gauge size and position, stations closures and moves, previous bridging/infilling and updating of records. Table 3.3 lists years of break detection alongside metadata for each case. Years for which no explanation could be found are highlighted in bold. There is little consistency in timing of break detection throughout the network with 12 breaks occurring before 1941 (i.e. prior to transcribing) and 13 after.

Station	*Year of break (amplitude)*	Years n	Details from metadata
Cork Airport 1850-2010	1958 (+0.13)	161	Station record originally constructed by Tabony (1980) using a composite of stations. Prior to 1962 data is reported from University College Cork which is at a lower elevation and is likely to explain the detected break.
Birr 1850-2010	1851 (+0.27)	161	Station record originally constructed by Tabony (1980) using Birr and composite of stations up to 1971. Updated to 1994 by Jones and Conway (1997) and updated to 2010 using Birr station records from Met Éireann. Change from 15" to 5" gauge during 1850s may have caused detected break.
Malin Head 1891-2010	1924 (+0.13) 1966 (+0.10)	120	Station record originally constructed by Tabony (1980) using composite of stations up to 1975. Reading were made at the telegraphic reporting station (Lloyds tower at a height of 230ft. In 1921station moved to the coast guard station and at a height of approx 20ft above msl. From 1921-1940 readings were taken at 01.00, 07.00, 10.00, 15.00, 18.00 and 21.00 GMT but rarely all 6 times. From 1940 to 1950 only sporadic readings were taken at 04.00 and 13.00 GMT. 1950 reading times changed again to 0.600, 12.00 and 18.00 GMT. In May 1955 a new synoptic station opened, with subsequent readings taken on the hour.
Killarney 1862-2010	1980 (+0.13)	149	Station record originally constructed by Briffa (1984) from composite of stations up to 1980. Updated to 1994 by Jones and Conway, (1997). Valentia used in 1972-1976 to infill records and may have caused detected break.
Enniscorthy 1871-2010	***1888 (-0.10)***	140	Station record originally constructed by Briffa (1984) from composite of stations up to 1980. Updated to 1994 by Jones and Conway (1997). Break unexplained.
Belfast 1850-2010	1898 (+0.09) ***1945 (-0.09)***	161	Station record originally constructed by Tabony (1980) using composite of stations up to 1977. In 1902 the gauge moved to Royal Academic Institute where estimates were applied and may have been the cause of the detected break in 1898. No issues in metadata to explain break detected in 1945.
Mullingar 1876-2010	***1937 (+0.12)*** 1950 (-0.24)	135	No explanation in the metadata for break in 1937. Archived station Belvedere House, Mullingar closed in 1950 and was updated to 2010 using station records at Mullingar Town and may have caused break detected in 1950.
Rathdrum 1873-2010	1918 (+0.10)	138	Archived station at Rathdrum was infilled from donor station at Coolatin for the period 1918-1923 and may have been the cause of detected break.
Drumnsa 1893-2010	1917 (-0.22) 1941 (+0.40)	118	Missing months infilled from Strokestown 1921 and 1949. These years and 1938 considered too low. 1939 records of Drumsna never appeared in British rainfall. 1942 5" gauge 1' above ground leaking. Very exposed open flat country. Partly shaded by fencing. New gauge installed in sheltered position nearby for comparison. 1943 new gauge now official instrument.
Shannon Airport 1861-2010	1930 (-0.07)	150	Station record originally constructed by Tabony (1980) using composite of stations up to 1977. Change from an 8" to 5" gauge in 1930.
Roches Point 1890-2010	***1956 (-0.1)*** 1990 (+0.16)	121	Station record originally constructed by Tabony (1980) using composite of stations to the 1970s. Updated to 1990 by Jones and Conway (1997). Bridged to 2010 using Cork Airport which may have caused the detected break in 1990. Limited metadata with no issues that may have caused detected 1956 break.
UCG 1862-2010	1874 (-0.21) 1907 (-021) 1920 (+0.22) 1933 (-0.13) 1952 (+0.18) ***1987 (+0.10)***	149	Metadata show low values recorded in 1875, 1907, 1920, 1921 and 1933 which may be due to observer data entry errors. Up to 1951 the values had been recorded in inches but changed in 1952 to millimetres and could have been converted incorrectly which may explain the detected break in 1952. New station opened 1965 but no issues are identified to explain the break in 1987.
Portlaw 1850-2010	1941 (-0.10) 1965 (+0.12)	161	Metadata show that from 1940s to the late 1960s several issues occurred. The rain gauge had to be replaced several times due to damage and faults. The observer was also using a mm rain-measure and dividing by 2 to convert to inches. In addition, over this period vegetation was high and too close to gauge which may have caused undercatch.
Ardara 1870-2010	1983 (+0.07)	141	Station originally constructed by Briffa (1984) from composite of stations up to 1980. Updated to 1994 by Jones and Conway (1997) may have caused detected break in 1983.

Table 3.3 Detected break points across 14 stations showing year and amplitude of break point, number of years in the series tested and associated metadata. Breaks shown in bold have no explanation in metadata.

Overall break detection frequencies are consistent with other studies in Europe (e.g. Domonkos, 2014 and references therein). Low break detection frequencies, particularly in early parts of the record are testimony to the quality of work by Tabony (1980) and Briffa (1984) in constructing composite series. The amplitude of detected breaks is also presented in Table 3.3. Amplitude provides an indication of the magnitude of breaks detected as well as the amount of adjustment needed to correct the inhomogeneity. Across all stations and detected breaks the mean absolute amplitude was 0.15. The largest break (amplitude 0.40) was found for Drumsna in 1941 and associated with a leaky gauge and position changes (Table 3.3). The smallest break (amplitude 0.07) was found in 1930 at Roches Point and associated with a change from an eight inch to a five-inch gauge.

Five breaks could not be explained by the metadata. Rather than blindly apply adjustments, these cases were further investigated by employing the Mann Kendall test to examine the persistence of trends for uncorrected series relative to trend persistence for the fully homogenised network (Figure 3.4). Attention was paid to two aspects: i) persistence of trends relative to the pattern of change across the network as a whole; and ii) notable changes in trend persistence for individual stations before and after detected change points. Large deviations from trends in the homogenised records emerged. For Mullingar tests commencing before the identified break point in 1937 show persistently significant negative trends; after the break point positive trends are found. Other large deviations in trend persistence around identified break points are found for Belfast, Enniscorthy and Roches Point. Given the proximity of the break at UCG to the end of record this was more difficult to assess, however, confidence in this break is increased given the very high MK Zs scores for tests commencing after 1950 together with the number of previously verified breaks (5) for this record. Given the suspicion raised, all breaks (confirmed and unconfirmed by metadata) were subject to adjustment.

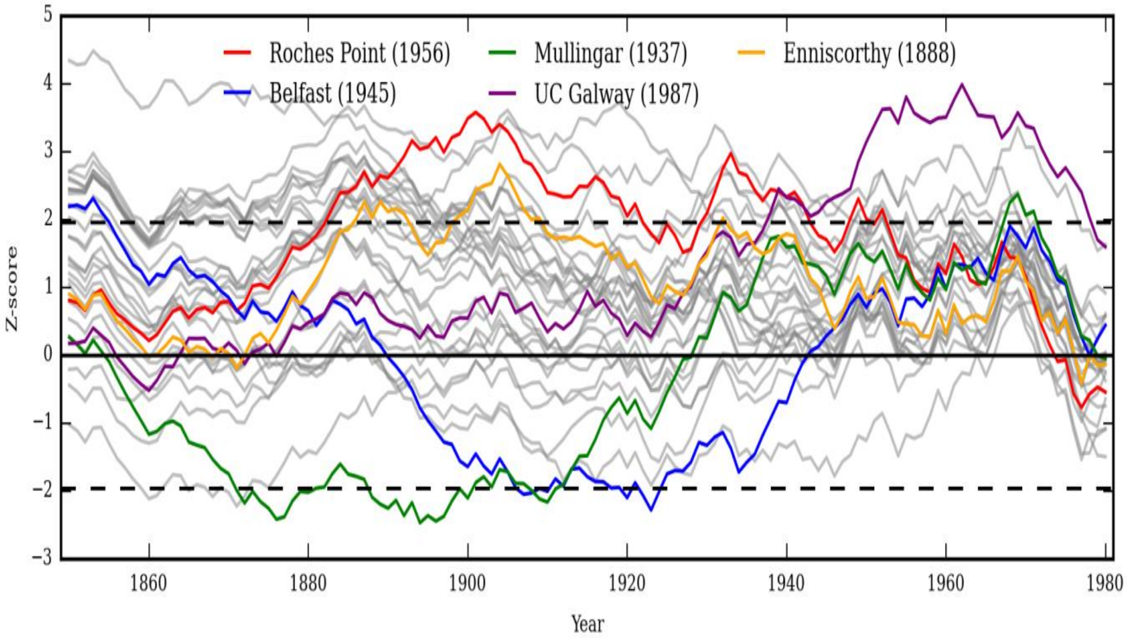


Figure 3.4 Persistence of trends for stations with breaks unconfirmed by metadata relative to the persistence of trend for fully homogenised records for all 25 stations (grey lines and including 11 stations with no breaks detected). Dotted horizontal lines represent critical values beyond which trends are significant at 0.05 level

Detected breaks were corrected annually with multiplicative adjustments relative to the break amplitude applied equally across monthly series. This decision was made as the HOME COST action found the application of yearly corrections by PRODIGE to be more stable and accurate, and hence these are currently recommended for homogenisation of precipitation networks (Venema *et al*., 2012). In a maritime climate such as Ireland variability of precipitation from month to month is low enough to allow such correction. In addition, Auer *et al.* (2005) and Moisselin and Canellas (2005) recommended that the same annual adjustment factor be applied to all months.

3.3.2 Quality Assurance of Homogenised Series

While homogeneous series are defined as those where variability is only caused by changes in weather or climate (Freitas *et al*., 2013), characterisation of homogeneity depends on the objectives of the study, the tests used and decisions made when applying methods. In relative homogenisation, as applied here, the most fundamental issue is selection of reference series for assessment of breaks at the candidate station (Auer *et al*., 2005). Previous experience recommends that at least 50% shared variance (r^2) is needed between candidate and reference series (Scheifinger *et al.*, 2003; Auer *et al*., 2005). At lower levels, detection of discontinuities can be hampered by statistical noise. The scarcity of long records means that station density is relatively low across the island, yet extension to a common period required selection of 12 reference stations for each candidate to avoid issues of excessive missing data. Both of these objectives have the potential to lessen the availability of strongly correlated reference stations.

Table 3.2 reports correlation coefficients for identified reference stations for each candidate. However, mean reference network correlations for Derry, UCG, Ardara and particularly Malin Head (mean r = 0.58) fall below the recommended correlation threshold of 0.71 (i.e. $r^2 = 0.50$) (Scheifinger *et al.*, 2003; Auer *et al*., 2005).Therefore sensitivity of break detection to network density is assessed by re-running HOMER for candidate stations using a finer density network for the period 1941-2010. In the main, consistency of break detection frequency and timing add confidence to results. However, two minor differences resulted. First, a change in year of break is found at Malin Head from 1966 to 1955 (1941-2010) with the latter break more in line with metadata. Second, at Drumsna two new breaks are detected in 1965 and 1968 in the 1941-2010 run. Metadata reveals concern over a defective gauge in 1968. In 1967 the gauge is reported as being in good order while in 1969 the gauge is replaced (See appendix 3.1).

Following homogenisation the Pettitt (1979) test was applied to annual series for each IIP station to check for residual breaks. From Figure 3.5 a consistent upward change point in the early 1920s is apparent for many stations and significant (p-values < 0.05) at Strokestown, Markree Castle, Athboy, Malin Head and Mullingar. The consistency of timing and direction of these, in the absence of evidence for changes in measurement techniques across the island at this time, increases confidence that such changes are climatically driven. There is no evidence from metadata to raise suspicion of a simultaneous change in measurement practice at this time.

However, caution has to be flagged at Malin Head where a break (associated with station move) is also detected (and corrected) by HOMER in 1924. Given the low mean *r* of this candidate with reference stations the amplitude of detected break may be prone to error. Significant upward change points are also detected at UCG (1915), Ardara (1933) and

Drumsna (1933) with the annual series for each presented in Figure 5. At UCG little metadata is available but note that the detected break is small in relative terms with a 3.5% increase in mean annual precipitation for the post 1915 record. It also noted that no change in trend persistence at UCG around 1915 (Figure 3.5).

The Pettitt test revealed a more complex situation at Ardara and Drumsna where a simultaneous break point is detected in 1933. Drumsna is part of Ardara's reference network for pairwise detection and vice versa. Metadata reveals independent issues at both stations in this year which is problematic for relative detection methods with the consequence that HOMER may have missed an artificial break in both series. The Drumsna gauge is known to underestimate rainfall prior to 1940. HOMER detected and corrected a break in 1944. At Ardara, Briffa (1984) applied a large bridging correction factor (+1.57) between 1932-34.

However, 1933 is also a notable drought year being second driest in the IIP (see below) and Drumsna series and driest at Ardara. Absolute changes in mean annual precipitation for records after 1933 are also very similar with a 5.8% and 5.3% increase evident for Drumsna and Ardara respectively. Given this complexity caution is also flagged for both these series. For all three series (UCG, Ardara and Drumsna) the absolute magnitude of breaks are small and there is no evidence for major changes in trend persistence around these years. Little evidence was found from metadata that breaks were missed by HOMER. For Markree Castle, Waterford and Phoenix Park there is reference to gauge position and height changes early in the record that are not detected by HOMER or the Pettitt test.

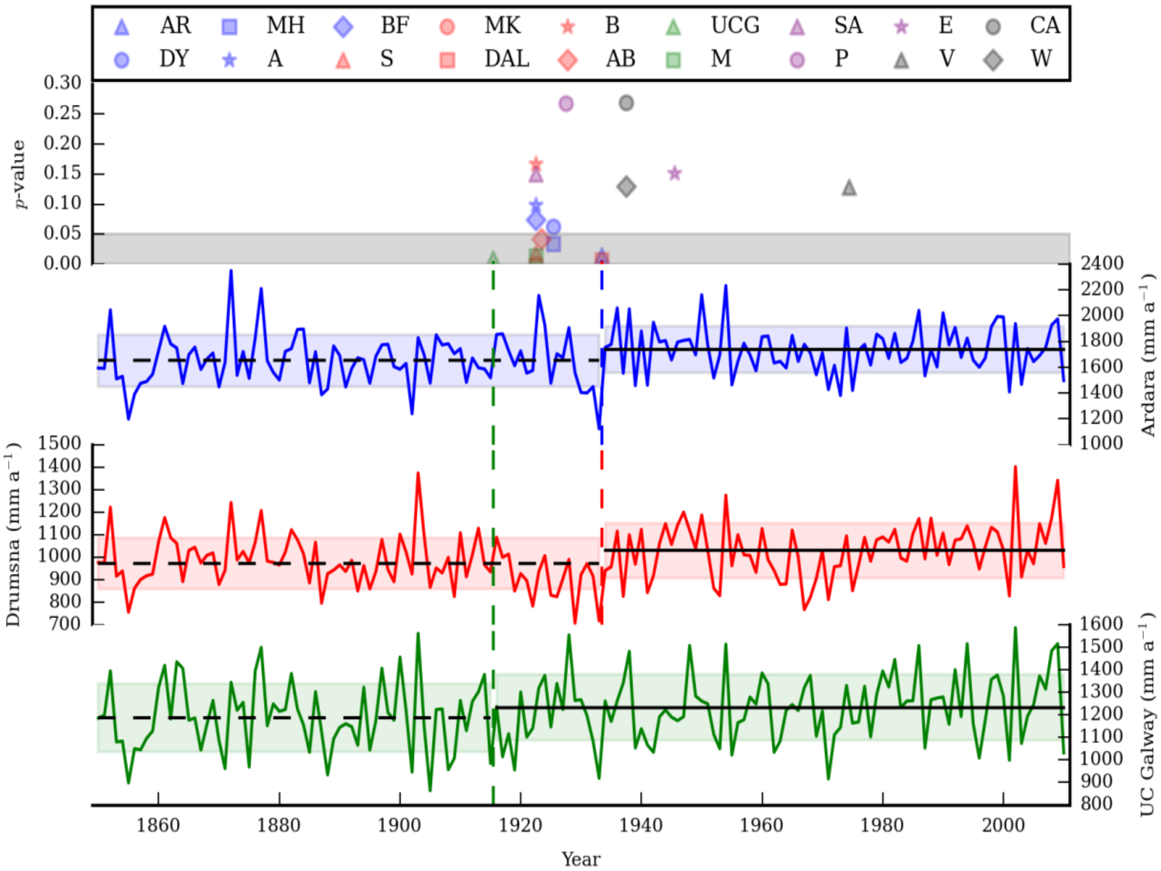


Figure 3.5 Top: Pettitt test for change points in mean annual precipitation. The grey shaded region indicates the region in which p-values are interpreted as significant (0.05 level). Time series plots (lower 3 axes) illustrate the mean annual precipitation at the stations with significant change points outside the 1920s (see text for further detail). These change points are highlighted with dotted vertical lines; the colours of which correspond to the respective time series. Note that Ardara and Drumsna both have change points in 1933, hence the blue and red dotted lines are over-plotted. The dotted (solid) black horizontal lines illustrates mean values before (after) the identified change point; the shaded region spans ± 1 standard deviation.

3.3.3 Variability and change in the IIP network

Variability and change was assessed across the catalogue of 25 HOMER homogenised rainfall series. Figures 3.6, 3.7 and 3.8 present annual, winter (DJF) and summer (JJA) smoothed series for each station along with trend persistence for both homogenised (1850-2010) and non-homogenised series (start year to 2010). In smoothing series an 11-year moving average was used to highlight low-frequency variability. For stations revealing breaks, MK Zs statistics before/after homogenisation show large differences in trends. At Mullingar the trend in annual precipitation changes from significant (0.05 level) negative to significant positive. At Killarney, Cork, UCG and Malin Head, exceptionally large MK Zs scores in annual precipitation are removed following homogenisation. Such differences highlight the importance of this work in increasing the confidence with which variability and change within the network can be assessed following homogenisation.

For annual indices the majority of stations show non-significant positive trends throughout the record. However, Killarney, Cappoquinn and Foulkesmills show negative trends for long records. The greatest number of significant (0.05 level) trends was found for tests commencing in the 1880s, with trend significance highly dependent on period of record tested. In winter, with the exception of Foulkesmills, Cork Airport and Cappoquinn, long records show a tendency for positive trends. The strongest positive trends are found for Markree Castle, Malin Head and Ardara with significant (0.05 level) trends found for records commencing before 1890 for these stations. However, in winter shorter records are not representative of longer-term trends with all stations showing negative trends for records commencing after 1980.

In summer, long records show a tendency for negative trends, with significant (0.05 level) trends found for stations in the south and east (Killarney, Cappoquinn, Enniscorthy, Foulkesmills, Athboy and Rathdrum) for tests commencing before 1880. Again, shorter records are not representative of long term trends. For tests run from the mid-1950s onwards all stations show positive trends, many of which are significant from the mid-1960s to mid-1970s.

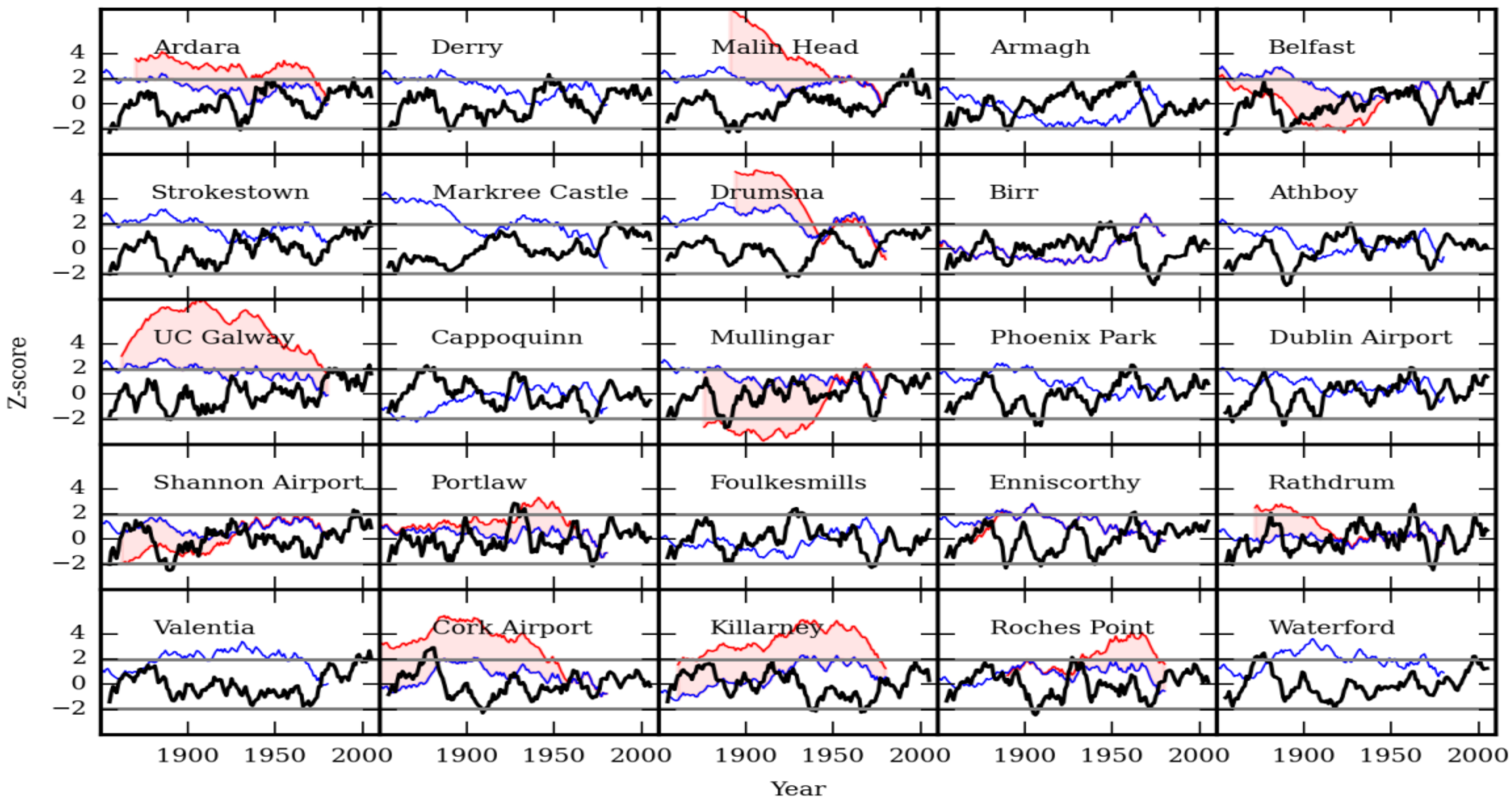


Figure 3.6 Homogenised annual time series for all stations smoothed with an 11-year moving average (black line). MK Z scores are shown before and after homogenization where applicable (red: unhomogenised; blue: homogenised/no breaks detected) calculated for varying start years (which are given by the x-coordinate). The grey lines indicate ±1.96; absolute values exceeding these bounds are interpreted as significant at the 0.05 level.

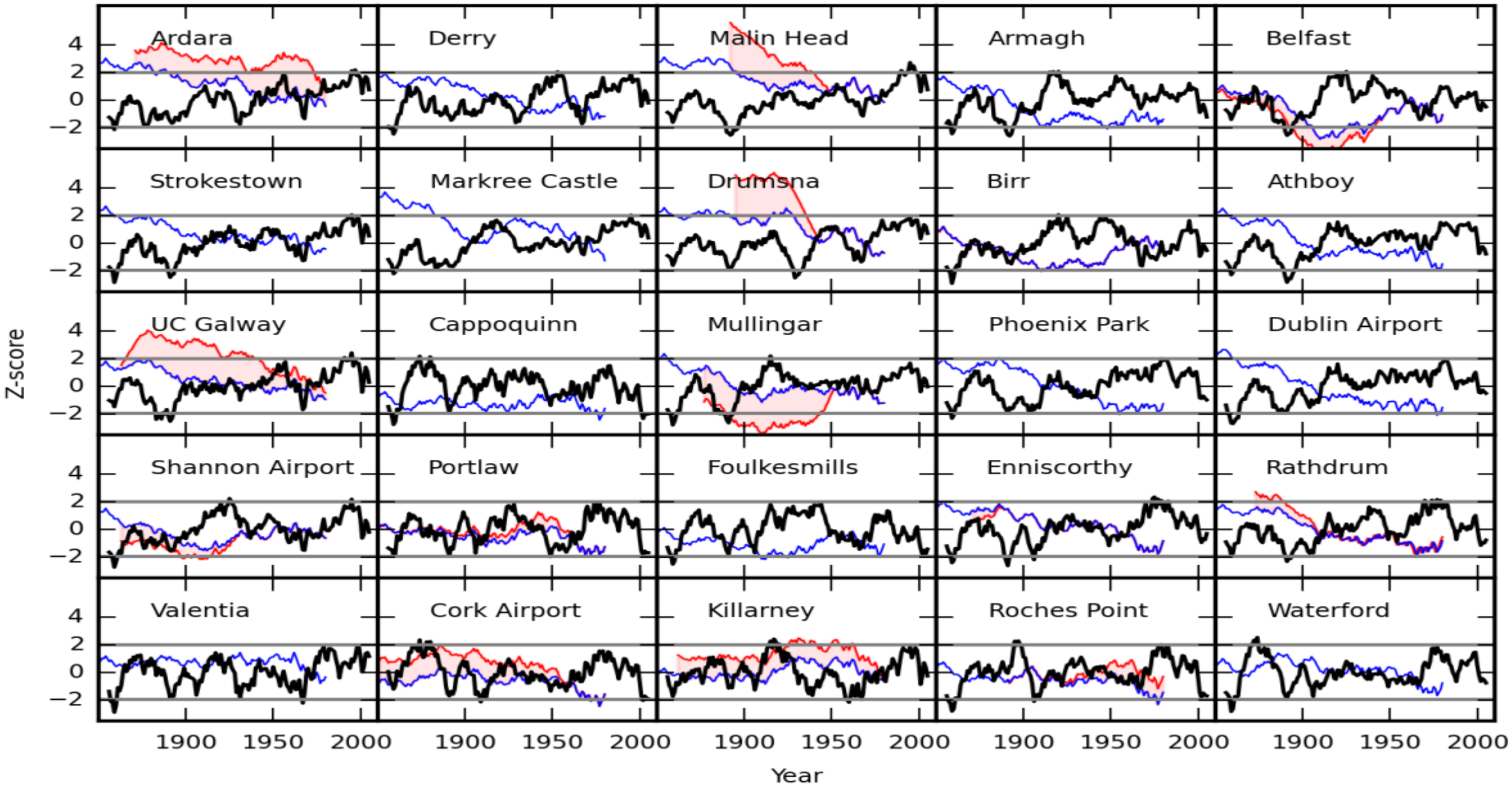


Figure 3.7 Homogenised winter time series for all stations smoothed with an 11-year moving average (black line). MK Z scores are shown before and after homogenization where applicable (red: unhomogenised; blue: homogenised/no breaks detected) calculated for varying start years (which are given by the x-coordinate). The grey lines indicate ±1.96; absolute values exceeding these bounds are interpreted as significant at the 0.05 level.

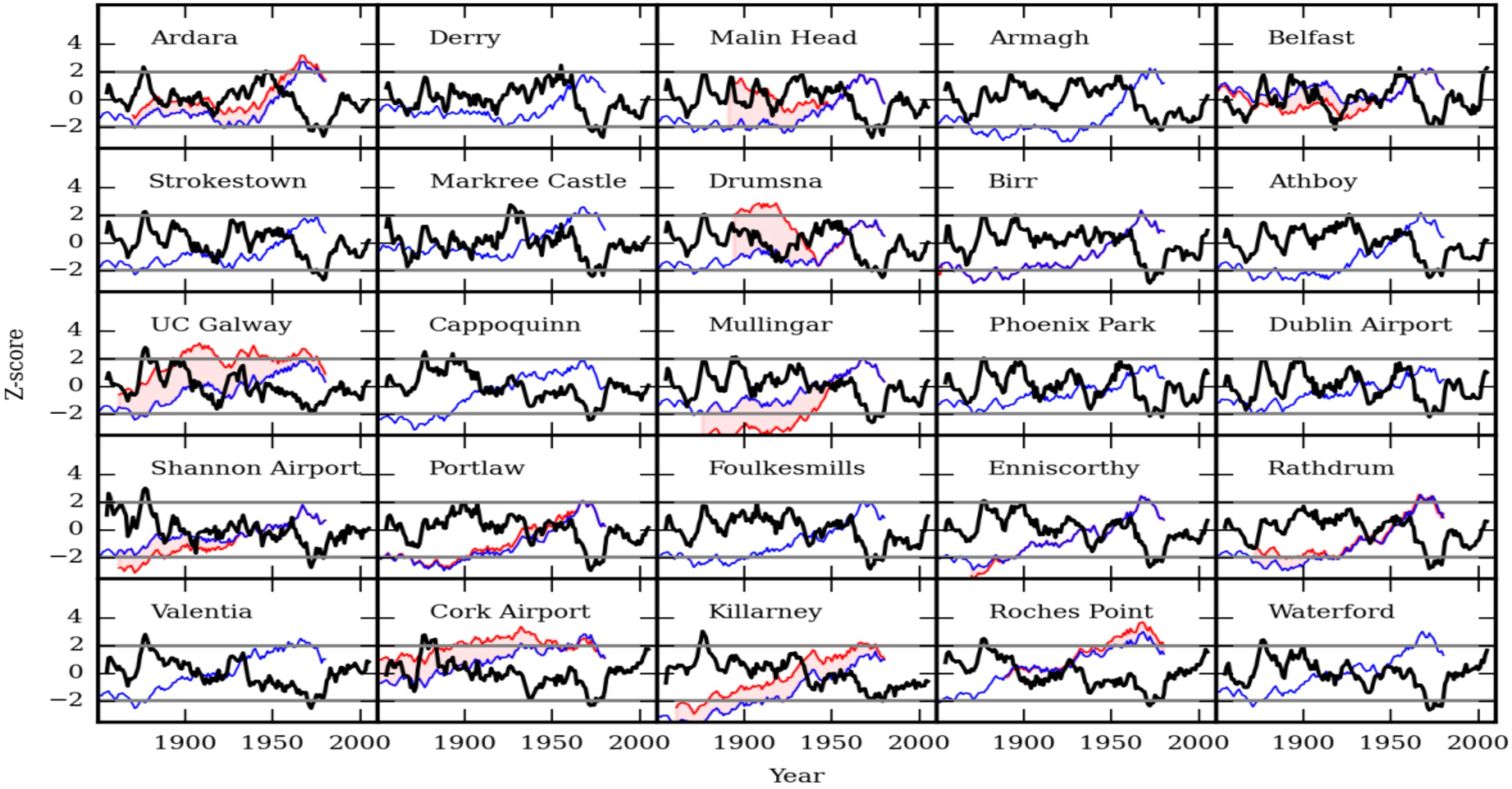


Figure 3.8 Homogenised summer time series for all stations smoothed with an 11-year moving average (black line). MK Z scores are shown before and after homogenization where applicable (red: unhomogenised; blue: homogenised/no breaks detected) calculated for varying start years (which are given by the x-coordinate). The grey lines indicate ±1.96; absolute values exceeding these bounds are interpreted as significant at the 0.05 level.

The notable years were assessed both seasonally and annually for the extended and homogenised network. Table 3.4 shows the wettest/driest years for each station. On an annual basis the exceptionally wet years 2002 and 1872 stand out. Year 1872 was the wettest at Ardara, Derry, Cappoquinn and Waterford with 2002 being wettest at Belfast, Strokestown, Drumsna, UCG and Dublin Airport. 1887 is the most frequently identified driest year (6 stations), followed by 1933 (4 stations) and 1893 (3 stations).The years 1891 and 1964 rank as those with the driest winters in nine and six stations respectively. Years 1877, 1994 and 1995 stand out as wettest ranked winters across 12 stations. In summer, 1995 is driest at 6 stations (Armagh, Athboy, Phoenix Park, Foulkesmills, Enniscorthy and Rathdrum) while 1976 is driest at Belfast, Birr and Mullingar. In terms of wettest summers, 1861 ranks top across 8 stations located along the west coast while 1958 is wettest for stations in the east. Latter years of the 2000s also stand out because of wet summers (in 2007, 2008 and 2009). Spring 1947 was the wettest for 15 stations with both 1995 and 1976 notable as the driest springs.

3.3.4 Variability and change in the IIP Series

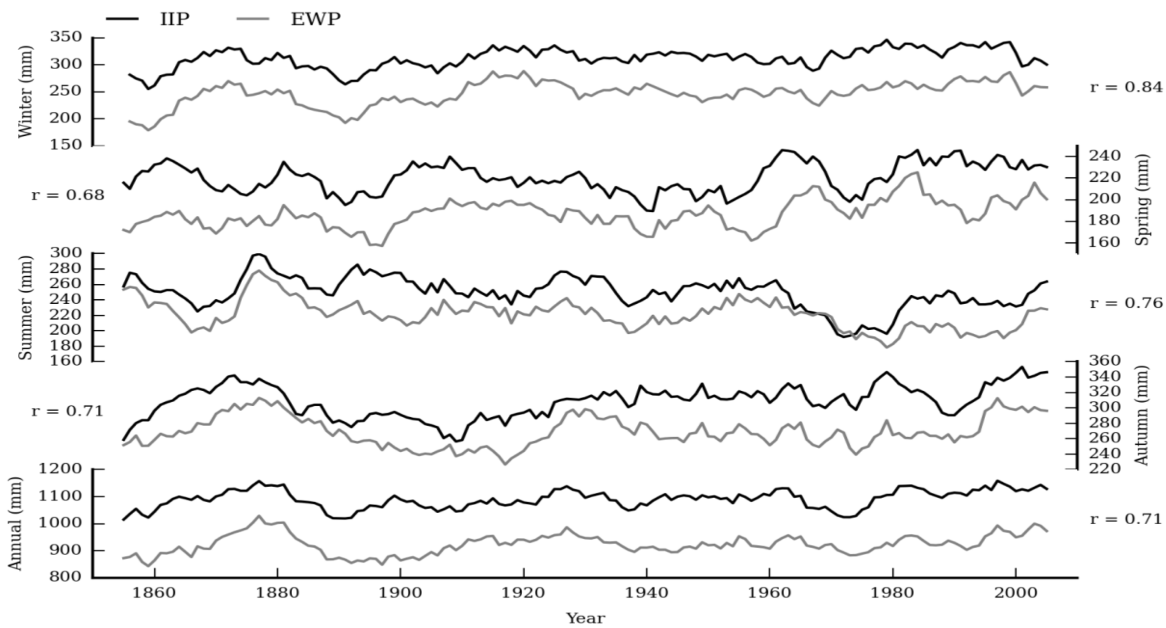


Figure 3.9 Comparison of smoothed (11 year moving average) Island of Ireland Precipitation (IIP) and England and Wales Precipitation (EWP) (mm) for the common period 1850-2010. Plotted from top are winter, spring, summer, autumn and annual series. Also shown are Spearman's rank correlation coefficients.

Figure 3.9 shows an annual and seasonal comparison between the smoothed (11-year-moving-average) IIP and England and Wales Precipitation (EWP) series for the period 1850-2010. Of note is the close correspondence of series across all seasons. Table 3.5 shows the ranks of seasonal and annual wettest and driest years for the IIP series. The wettest year in the 161 year record is 1872 with wettest seasons being 1994 (winter), 1947 (spring), 1861 (summer) and 2000 (autumn). In the EWP series for the period analysed 1872 is also the wettest year while in winter 1994 ranks 4th wettest; 1947 ranks 2nd in spring. The wettest summer in the EWP series for 1850-2010 is 1912 which ranks 4th in IIP. In both series 2000 is the wettest autumn in the period. The 1870s feature frequently in the wettest ranks for the homogenised IIP series.

In addition to 1872 being the wettest year, 1877 ranks as the 7th wettest year and the 5th wettest winter, 1879 is the 3rd wettest summer and 1875 the 4th wettest autumn. The 2000s also feature strongly in the ranks for wettest summers and autumns. The sequence of very wet summers in Ireland in 2007, 2008 and 2009 rank as 8th, 2nd and 4th wettest summers respectively over 1850-2010. For IIP the driest year is 1887 which ranks 2nd in EWP, while the driest summer is 1995 in both series for the period 1850-2010. Spring 1893 is the driest in both series. For the IIP record 1933 is the driest autumn while the driest winter was recorded for 1891 followed by 1964.

Strong correspondence is also evident with the storminess indices produced by Matthews *et al.* (2015) for the British-Irish Isles. Year 1872 (wettest year in IIP series) ranks as the stormiest year in the period to 2010 and is explained by exceptionally high cyclone counts for the region. The second and third wettest years in the IIP series (2002 and 2009 respectively) also rank highly in terms of storminess. Further similarities with Matthews *et al.* (2015) include 1915 being ranked as the stormiest winter and 4th wettest in the IIP series. Autumn 2000 ranks as the wettest for IIP and highest for cyclone counts. Spearman's rank correlation coefficients were derived for annual and seasonal IIP series and the corresponding NAO index (NAOI) (i.e. winter IIP and winter NAOI etc.). Statistically significant (0.05 level) but weak positive correlations are found for winter (r = 0.295), spring (r = 0.202) and autumn (r = 0.116). IIP summer precipitation is significantly and negatively correlated with summer NAOI (r = -0.154). A positive but non-significant correlation is found between annual NAOI and annual IIP (r = 0.116).

	Winter		Spring		Summer		Autumn		Annual	
Station	*Wettest*	*Driest*	*Wettest*	*Driest*	*Wettest*	*Driest*	*Wettest*	*Driest*	*Wettest*	*Driest*
Ardara	1937	1963	1986	1929	1861	1984	1954	1933	1872	1933
Derry	1994	1891	1907	1929	1956	1885	1872	1915	1872	1933
Malin Head	1995	1891	1916	1900	1861	1900	1967	1894	1954	1900
Armagh	1877	1891	1947	1870	2007	1995	1870	2007	1852	1933
Belfast	1877	1964	1947	1875	2007	1976	1954	1933	2002	1855
Strokestown	1994	1891	1947	1929	1861	1913	1954	1933	2002	1921
Markree	1995	1964	1985	1852	1861	1864	1917	1856	1924	1864
Drumsna	1994	1964	1947	1929	1861	1909	1954	1922	2002	1929
Birr	1995	1964	1947	1915	2007	1976	2000	1912	1946	2003
Athboy	1994	1891	1947	1893	1958	1995	1944	1893	1924	1893
UC Galway	1995	1891	1986	1918	1879	1940	1954	1871	2002	1905
Cappoquinn	1883	1992	1931	1893	1903	1909	1875	1919	1872	1921
Mullingar	1915	1891	1947	1953	1861	1976	2000	1922	2002	1887
Phoenix Park	1979	1891	1947	1929	1958	1995	1960	1904	1958	1887
Dublin Airport	1979	1964	1947	1929	1958	1887	2002	1904	2002	1887
Shannon Airport	1995	1964	1994	1893	1861	2006	2000	1933	2008	1933
Portlaw	1966	1855	1931	1896	1903	1869	2006	1919	1903	1887
Foulkesmills	1912	1907	1947	1990	1912	1995	1875	1978	1928	1887
Enniscorthy	1966	1855	1947	1893	1997	1995	1875	1969	1960	1893
Rathdrum	1966	1891	1947	1893	1958	1995	1960	1893	1966	1893
Valentia	1915	1934	1913	1893	2009	1940	2000	1932	2009	1971
Cork Airport	1883	1855	1947	1990	1878	1869	1881	1942	1881	1854
Killarney	1995	1963	1903	1893	1861	2006	1916	1922	1861	1971
Roches Point	1900	1992	1947	1990	2008	1909	1960	1919	1928	1887
Waterford	1912	1855	1947	1893	1997	1913	2006	1919	1872	1893

Table 3.4 Seasonal and annual wettest and driest years for each station in the extended and homogenised IIP network 1850-2010.

Variability of trends within the IIP series was examined using a moving windows approach to assess trends across all possible start and end dates (minimum of ten years). The resulting trends in seasonal precipitation for the IIP series are presented in Figure 3.10. For winter long records show positive trends; however, significant (0.05 level) trends are only associated with tests commencing before 1860. As with station based analyses, shorter records are not representative of longer term trends. For tests commencing after 1910 negative trends are evident for the winter IIP series. For spring, the full record length shows weak positive trends with the direction and significance of trends dependent on period of analysis. Significant positive trends are found for tests commencing between 1930 and 1940. In summer, long records show significant (0.05 level) negative trends. These trends only become significant for tests ending after the 1970s. Again the period of record is critical with tests commencing after the 1970s showing positive trends. Finally, positive trends are found for all start years in autumn, however significant trends are only returned for series commencing between 1880 and 1910.

	Winter		**Spring**		**Summer**		**Autumn**		**Annual**	
Rank	***Wettest***	***Driest***	***Wettest***	***Driest***	***Wettest***	***Driest***	***Wettest***	***Driest***	***Wettest***	***Driest***
1st	1994	1891	1947	1893	1861	1995	2000	1933	1872	1887
2nd	1995	1964	1981	1990	2008	1913	2006	1922	2002	1933
rd	1883	1855	1913	1929	1879	1869	1954	2007	2009	1855
4th	1915	1934	1986	1944	2009	1870	1875	1919	1852	1971
5th	1877	1953	1920	1887	1912	1976	1982	1912	1928	1893
6th	1966	2006	1897	1915	1958	1975	1944	1879	1903	1975
7th	1990	1858	1993	1975	1860	1983	1960	1854	1877	1953
8th	1869	1874	2002	1984	2007	1940	2002	1855	1960	1921
9th	1937	1963	1862	1875	1985	2006	1916	1893	1924	1854
10th	1974	1888	2006	1938	1852	1959	2009	1942	1958	1919

Table 3.5 Top 10 ranked wettest and driest seasons and years from the homogenised and extended Island of Ireland precipitation (IIP) series 1850-2010

In summary, for both the IIP and individual station series there are few persistent trends evident with the magnitude, direction and significance of trends highly dependent on the period of record in all seasons due to strong inter-decadal variability. For the typical period of record available for digitised data, trends in winter and summer are not representative of results from longer records, while even shorter records commencing from the 1960s onwards show negative (positive) trends in winter and summer. Coherence in the temporal evolution of trends across all stations for both annual and seasonal indices increases confidence in the homogeneity of the network, as does the close correspondence with the England and Wales precipitation series and storminess indices of Matthews *et al*. (2015).

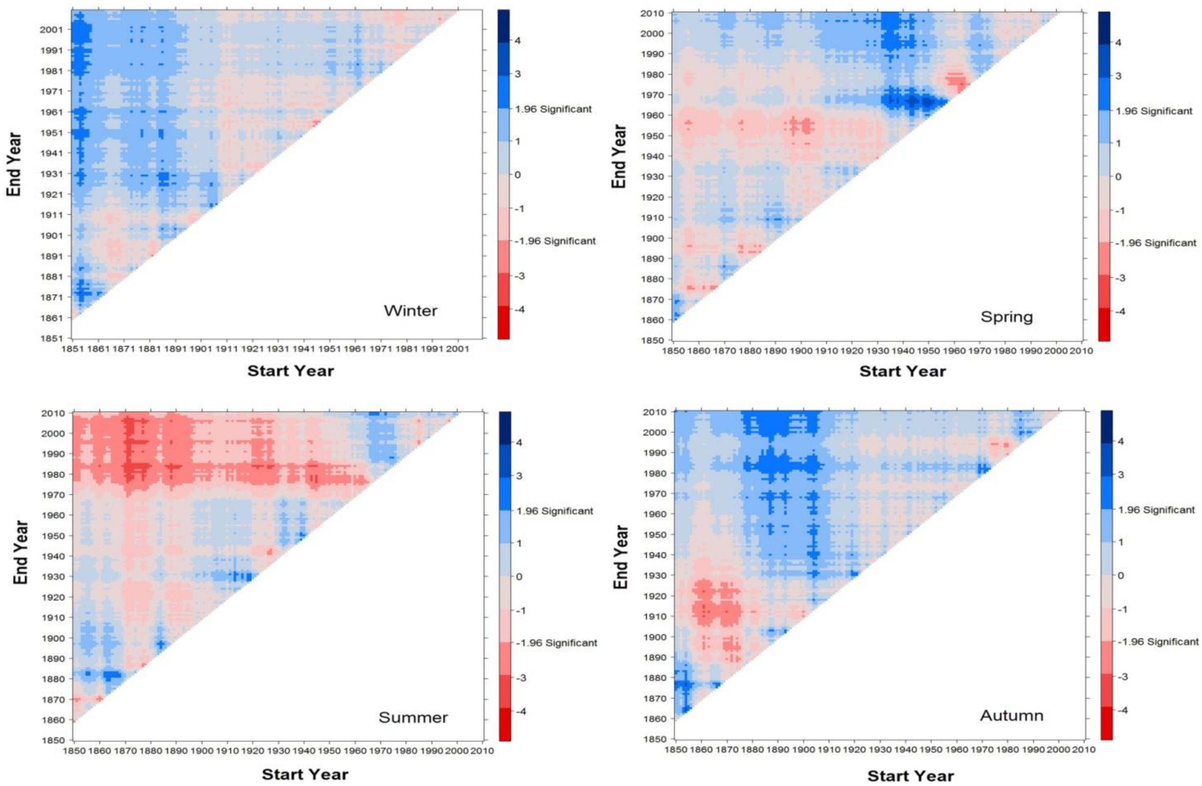


Figure 3.10 Moving windows trend tests for seasonal Island of Ireland Precipitation (IIP) series. Trends calculated using the Mann Kendall test with MK Z statistic plotted for all combinations of start and end years (minimum of ten years). Significant (0.05 level) trends have a MK Zs > |1.96|. The y-axis denotes start year and x-axis the end year of analysis. Blue indicates positive trends; red negative trends.

3.4 Chapter Summary

This chapter has constructed an extended Island of Ireland Precipitation (IIP) archive for the period 1850-2010 using a suite of homogenisation techniques. The resulting network, comprising 25 stations together with a composite series for the Island of Ireland, highlights the vital importance of long-term records in contextualising climate variability and change. Regionally, the derived IIP series is second in longevity only to the EWP series; hence its addition to the research field offers rich opportunities to understand long-term variability at the scale of the British-Irish Isles - a sentinel maritime location on Europe's Atlantic coast. Correspondence between detected breaks and available metadata demonstrate the value of applying qualitative and quantitative techniques in parallel. Following homogenisation and adjustment of detected breaks using HOMER the assessment of variability and change over the period 1850-2010 indicates positive trends in winter and negative trends in summer precipitation. Trends in records covering the typical period of digitisation (1941 onwards) were not always representative of trends since 1850. Furthermore, results post-homogenisation revealed changing magnitude and even direction of trends at some stations.

While cautionary flags are raised for some stations, confidence in the derived series is increased by collating metadata for each station, by coherence of trends across the network, and by consistency with the England and Wales Precipitation series (Alexander and Jones, 2001), cyclone metrics derived for the British-Irish Isles (Matthews *et al*., 2015) and consistency with the North Atlantic Oscillation Index (NAOI). For transparency this study provides all available metadata as supplementary information (Appendix 1) and encourages this as standard practice in homogenisation studies.

There is much scope for developing this initial work. Further stations could be added to the network by recovering additional hardcopy data from the archives using the methods adopted here. This would be particularly important for increasing confidence in the homogeneity of early parts of the record and for increasing confidence in break detection for stations with low correlations among reference networks. As an artefact of availability of long records there is also spatial bias in the IIP network that such future work could address.

Finally, this chapter shows the sense of advancing understanding of Irish climate on an all island basis using a network that could have wide utility in future research and in delivering improved baseline data for climate services. To this end the dataset produced here is freely available for use and download at www.met.ie/download/Long-Term-IIP-network.zip or by email with the author. As far as known, this work represents the first application of HOMER to a long-term precipitation network and bodes well for use in other regions.

This chapter has address **thesis objectives 1, 2 and 3**. **Objective 1:** Chapter 3 has expanded and extended the existing long term monthly rainfall catalogue by identifying and digitising suitable, hard copy archived monthly rainfall records held in Met Éireann's archives. In addition, detailed metadata and station history have been compiled and made available for future research. **Objective 2:** This chapter has meticulously checked the precipitation records for homogeneity using state of the art methods and detailed station metadata and station notes. **Objective 3:** Chapter 3 has also conducted a comprehensive analysis of how rainfall has changed in Ireland at the longer time scale. This chapter has also analysed long term, quality assured precipitation records for evidence of trends while contextualising recent extremes.

The next chapter will deal with **thesis objective 4.** Chapter 4 will further analyse the long-term precipitation records to produce a detailed historical drought catalogue for Ireland, Furthermore, qualitative historical documentary evidence will be accessed from available sources to validate the results and add confidence to the results.

4 A 250 year drought catalogue for the island of Ireland (1765-2015)

4.1 Introduction

Recent decades have witnessed severe drought events across Europe (Fink *et al.,* 2004; Lennard *et al.,* 2014; Todd *et al.,* 2013; Spinoni *et al.,* 2015; Marsh, 2004) with serious impacts including reductions or loss of water supply, decreased agricultural production and power generation, environmental degradation and even loss of life (Cole and Marsh, 2006; Briffa *et al.,* 2009; Hannaford *et al.,* 2011; Lennard *et al.,* 2014). Appropriate drought planning, particularly in the context of future climate change begins with understanding the magnitude and socio-economic impacts of past events. To this end a growing number of studies are using long-term observations alongside documentary evidence to identify and assess historical droughts (Mishra and Singh, 2010; Gosling *et al.,* 2012; Watts *et al.,* 2012; Lennard *et al.*, 2014; Lennard *et al.,* 2015; Kingston *et al.*, 2015).

For example, Marsh *et al.* (2007) and Cole and Marsh (2006) identify periods of prolonged drought in the UK during 1854-1860 and 1890-1910 - which were attributed to sequences of dry winter and summer seasons. Using long term observations (1697-2011) Todd *et al*., (2013) reconstructed droughts across the southeast UK, identifying several drought rich periods including 1943-1950 and 1970-1978. Spraggs *et al*. (2015) identified long drought periods in the 19th Century, with the most notable being 1854-1860 for the Anglian region (UK). Barker *et al*. (2004) reconstructed a 200-year precipitation series Central English Lake District, noting prolonged dry spells in the 1850s, 1880s, 1930s and 1970s.

Going back further in time, Brázdil *et al*. (2013) used documentary, proxy and instrumental sources to reconstruct droughts for the Czech Lands from 1090, identifying two important drought rich periods (in 1863-1874 and 2004-2012). Cook *et al*. (2015) constructed an "Old World Drought Atlas" (OWDA) dating from the 11th Century using instrumental records, tree-rings and documentary sources to identify mega-droughts and pluvials. Others have reconstructed long-term gridded monthly and seasonal precipitation records for Europe using proxy sources and long-term observational data sets (e.g. Casty *et al*., 2007). Casty *et al*. (2005) revealed that 1540, 1921 and 2003 were the three driest years in the last 500 for the European Alps. Pauling *et al*. (2006) find that the driest seasons in the past 500 years occurred in winter 1774, spring 1686, and autumn 1669 with extremely dry summers in 1666 and 1669. Despite their increasing availability, such long-term precipitation reconstructions have generally been under-utilised for drought assessment.

In Ireland, less detailed work has been conducted on historical droughts. Laoghog (1979) investigated the impacts of the severe drought of 1974-1976. Mac Cárthaigh (1996) analysed the 1995 drought from a water management perspective. Single-site analysis of drought at Armagh Observatory, highlights that the lowest rainfall amounts since records began in 1836 fell between April to August 1975 (Ó Laoghóg, 1979). Beyond recent experience, historical droughts were briefly discussed by Dooge (1985) for the period AD 759-1408. More recently, Wilby *et al*. (2015) examined the persistence of meteorological droughts using the Island of Ireland Precipitation (IIP) network 1850-2010 (Noone *et al*., 2015). This study demonstrated the potential for below average rainfall to persist for periods in excess of ten years, thus highlighting Ireland's vulnerability to long dry-spells.

To further understand historic droughts across the island of Ireland this research uses the IIP network to construct a detailed catalogue of drought events for the period 1850-2015. To extend this further this research employs available precipitation reconstructions for the period 1765-1849. Available documentary sources are integrated to (i) support the quantitative findings and (ii) explore the socio-economic impacts of notable droughts. Section 4.2 describes the datasets and methods employed; results are presented in section 4.3 with the main findings and future work discussed in section 4.4; the conclusions are set out in section 4.5.

4.2 Data and methods

4.2.1 Observed Rainfall 1850-2015

The Island of Ireland Precipitation (IIP) network (Noone *et al*., 2015) consists of homogenous monthly rainfall totals for 25 stations (Figure 4.1) and an Island of Ireland (IoI) series calculated as the arithmetic mean of all stations. Noone *et al*., (2015) used the HOMogenisation softwarE in R (HOMER) package (Mestre *et al*., 2013) and station metadata to homogenize and infill/extend all records for the period 1850-2010. Here, all stations in the IIP network and the IoI series are updated to December 2015 using data provided by the Irish meteorological service (Met Éireann). Where station closures have occurred or no data were available, bridging using correlated neighbouring station records was undertaken using linear regression (intercept of zero) to derive seasonal adjustments (as in Noone *et al.,* 2015). The updated IIP network and IoI series are employed to identify historic droughts over the period 1850-2015.

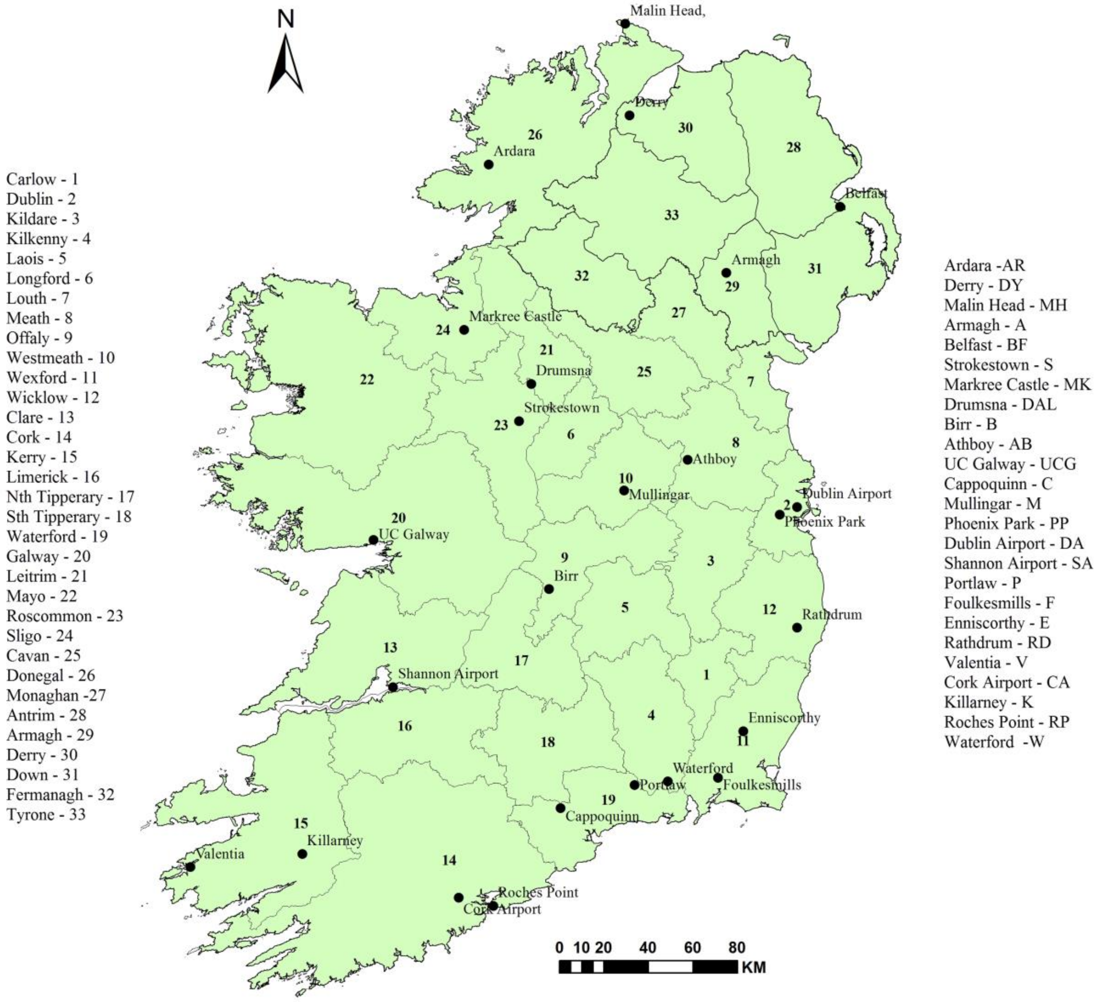


Figure 4.1 Location of the 25 stations in the Island of Ireland Precipitation (IIP) network and the abbreviated station names used later in later figures. Also shown are counties of Ireland to provide context for documentary references to locations.

4.2.2 Reconstructed Rainfall 1765-1849

Casty *et al*. (2007) provide gridded (0.5° x 0.5°) monthly precipitation reconstructions for the North Atlantic/ European area (80-30°N and 50°W-40°E) for the period December 1765 to November 2000. Pauling *et al*. (2005) describe the methods used to reconstruct the monthly precipitation which involved principal component regression techniques. The study used predictors such as long instrumental records and precipitation indices derived from documentary evidence and natural proxies (e.g tree-rings, ice cores, corals and speleothem) to reconstruct the precipitation (1500-1900). The study notes some reduced skill in reconstructions are present in some regions due to reduced predictor availability over certain periods (Pauling *et al*. 2005). Data from 1900 onwards being the gridded CRU TS2 reanalysis (Mitchell and Jones, 2005). To further extend the drought analysis, gridded precipitation reconstructions are extracted for the Irish land area to produce a composite series of monthly rainfall totals. Monthly regressions (intercept of zero) were derived for data overlapping the IoI series (1850-2000) and used to adjust the reconstructed to the homogenised IoI series. This extended monthly series (December 1765 to December 1849) are referred to as IoIext series. In assessing drought characteristics the IoIext series is analysed separately to the IIP network for 1850-2015.

4.2.3 Standardized Precipitation Index

The widely used Standardized Precipitation Index (SPI) (McKee *et al*., 1993; Guttman, 1999; Lloyd-Hughes and Saunders 2002; Redmond, 2002; Guttman, 1999; Van Loon, 2015) is used to identify drought events. This index was selected as it is applicable to monthly series, does not require additional climatological variables, and is recommended as a key drought indicator (WMO, 2012). The SPI is calculated by summing precipitation over specified accumulation periods (typically, 1, 3, 6, 9, 12 and 24 months) and fitting accumulation series to a parametric distribution from which probabilities are transformed to the standard normal distribution (McKee *et al*., 1993; Guttman, 1999; Lloyd-Hughes and Saunders, 2002). SPI values give standard deviations from typical accumulated precipitation for a given location and time of year. This allows the frequency, duration, intensity and magnitude of drought events to be quantified and compared even across climatologically different regions (McKee *et al*., 1993; Lloyd-Hughes and Saunders, 2002; Jenkins and Warren, 2015). SPI values between 0.99 and -0.99 are generally considered to be near normal, -1.00 to -1.49 is moderate drought, -1.50 to -1.99 is severe drought, and less than -2.00 is extreme drought (WMO, 2012).

Choice of accumulation period, reference period and statistical distribution are key methodological decisions when applying SPI. Shorter accumulation periods (1-6 months) are useful for examining agricultural drought, whilst longer durations (6-24 months) are more indicative of hydrological drought and water scarcity (WMO, 2012). Given the objective of examining impacts across multiple sectors this study derives SPI-12 using the '*SPEI*' package in R (Beguería and Vicente-Serrano 2013) to fit a gamma distribution to accumulated precipitation. Stagge *et al*., (2015) examined candidate distributions for SPI of various accumulations across Europe and confirmed the utility of the two-parameter gamma distribution for accumulation periods greater than one month. The SPI-12 was derived separately for reconstructed and observed series with normalisation performed relative to the median precipitation of their respective full records (i.e. 1765-1849 and 1850-2015).

4.2.4 Drought Identification

Following previous analyses, drought commencement is defined as the month in which SPI-12 falls below -1.00, with the return to positive values indicating the month of drought termination (Mishra and Singh, 2010; Lennard *et al*., 2014; Lennard *et al*., 2015). Variability in the drought climatology of the IoI composite series is examined by deriving 30 year accumulations of SPI-12 for identified droughts in all (over-lapping) 30 year periods from 1881-2015. Additional statistics were derived for each drought event, including:

Duration: number of months from commencement to termination
Accumulated deficit: sum of SPI-12 values during the event
Mean deficit: Accumulated deficit divided by drought duration
Maximum intensity: Minimum SPI-12 value achieved during the event

Given the focus on long droughts, these statistics are used to identify events in the IoI and IoIext series of greater than 18-month duration. Selection of 18 months allows this research to look in detail at droughts exceeding approximately the 80th percentile of all events in terms of duration. Given the impracticality of identifying uniform start and end dates for events across 25 stations, drought rich periods are examined in the IIP network. These are defined as years in which at least 40% of the stations in the IIP network experience drought events of at least 18-month duration.

4.2.5 Documentary Sources

Documentary evidence is used to confirm the occurrence of drought events and to examine their socio-economic impacts. Digitised and searchable historical print media are accessed through the Irish Newspaper Archive (www.irishnewsarchive.com). Sixteen national and regional titles are included (Table 4.1) which collectively spanned various political positions. Of particular note are the *Belfast Newsletter* and the *Freeman's Journal* which began reporting in the early and mid-18th Century respectively. A further nine titles commence in the 19th Century with many continuing to present day. Drought start and end dates identified from the SPI analysis were used to guide the search of newspaper archives for articles containing phrases such as 'drought', 'water shortage' or 'crop failure'. For inclusion in the analysis an article had to refer to drought explicitly in either the title or main text. Identified articles were saved by month and year of reporting and used to develop insight into the timing of drought development, associated impacts and responses to each event. Historical documents are also utilised including; the 1851 Census of Ireland (Wilde, 1851), Richard M. Barrington's assessment of the 1887 drought (Barrington 1888), the British Rainfall report for 1887 (Symons, 1887) and Whistlecraft's Rural Gleanings or Facts worth Knowing (Whistlecraft, 1851).

Title	Abbreviation	Start and end year	County	Publication Frequency
Belfast Newsletter	BN	09/01/1738 - 30/08/1890	National (NI)	Daily
Freeman's Journal	FJ	03/01/1763 - 19/12/1924	National	Daily
Kerry Evening Post	KEP	1813 - 1917	Kerry	Weekly
Tuam Herald	TH	13/05/1837 - Current	Galway	Weekly
Nenagh Tribune	NT	21/07/1838 - Current	Tipperary	Weekly
Irish Examiner	IE	30/08/1841 – 1999	National	Daily
The Nation	N	15/10/1842 - 05/06/1897	Dublin	Weekly
Tralee Chronicle	TC	18/03/1843 - 20/05/1881	Kerry	Daily
Anglo-Celt	AC	06/02/1846 - Current	Cavan	Weekly
Western People	WP	04/05/1889 - Current	Mayo	Weekly
Meath Chronicle	MC	01/05/1897 - Current	Meath	Weekly
Longford Leader	LL	14/08/1897 - Current	Longford	Weekly
Kerryman	K	20/08/1904 - Current	Kerry	Weekly
Irish Independent	II	02/01/1905 - Current	National	Daily
Connacht Tribune	CT	22/05/1909 - Current	Galway	Weekly
Irish Press	IP	05/09/1931 - 25/05/1995	National	Daily
Irish Framers Journal	IFL	16/03/1957 - 26/12/1998	National	Weekly
Irish Times	IT	1785 - Current	National	Weekly
Nenagh Guardian	NG	21/07/1838 - Current	Sligo	Weekly
Leinster Express	LE	24/09/1831 - Current	Offaly	Weekly

Table 4.1 Newspaper titles accessed through the Irish Newspaper Archive (www.irishnewsarchive.com) together with the abbreviations used in text, the start and end dates of publication, readership (national/county) and frequency of publication.

4.3 Results

4.3.1 Update of observations and extension using reconstructions.

Results of the IIP network update to December 2015, together with stations used for updating and the seasonal corrections applied are presented in Table 4.2. Of 25 IIP stations, 17 were updated by appending the 2011-2015 data to station records. For 8 stations, bridging to neighbouring gauges using seasonal regressions was necessary due mainly to station closures. Seasonal adjustments range from 0.79 at Enniscorthy for spring to 1.03 at Athboy for autumn. The largest mean actual error (MAE) (9.85 mm) is associated with the bridging of summer precipitation between Glenties (donor) and Ardara (IIP station). Following extraction of monthly precipitation for the island of Ireland from Casty *et al.*, (2007), data for the reconstructed period (1765-1849) were adjusted to the IoI composite series. Monthly adjustment factors derived for the overlapping period of 1850-2000 are shown in Table 4.3. Monthly adjustments are all within ±10 per cent, while July and November show largest MAEs.

IIP Station	Donor Station (overlap)	Winter			Spring			Summer			Autumn		
		r^2	*CF*	*MAE*	r^2	*CF*	*MAE*	r^2	*CF*	*MAE*	r^2	*CF*	*MAE*
Belfast	Hillsborough (1961-2010)	0.83	0.87	3.39	0.85	0.95	1.94	0.81	0.98	6.54	0.84	0.90	0.26
Birr	Victoria Lock (1941-2010)	0.63	1.01	2.10	0.82	1.05	-1.02	0.63	0.94	3.38	0.69	1.00	0.15
Ardara	Glenties (1941-2010)	0.77	0.89	-3.61	0.86	0.90	-3.02	0.87	0.87	9.85	0.89	0.89	0.49
Athboy	Delvin Castle (2000-2010)	0.72	1.08	3.55	0.86	1.10	1.90	0.51	0.89	6.54	0.92	1.03	0.25
Derry	Coleraine Cuts (1961-2010)	0.68	0.98	4.17	0.61	1.01	-2.11	0.64	0.97	6.98	0.62	1.00	0.30
UC Galway	Knock (1997-2010)	0.76	0.99	1.52	0.53	1.09	-0.76	0.65	1.02	2.64	0.63	1.00	0.11
Cappoquinn	Station House (2002-2010)	0.83	0.80	-0.79	0.76	0.79	-0.43	0.95	0.75	1.46	0.93	0.80	0.06
Enniscorthy	Bunclody (2002-2010)	0.87	0.82	2.41	0.90	0.85	-1.24	0.88	0.91	4.32	0.86	0.90	0.18

Table 4.2 Seasonal bridging results in updating 8 Island of Ireland Precipitation (IIP) network stations. Listed for each station is the neighbouring (donor) station used for updating, the seasonal correction factor (CF) used together with the coefficient of determination (r^2) and mean absolute error (MAE) (mm) for each seasonal regression (intercept zero).

Month	r^2	Adjustment factor	Mean Absolute Error (mm)
January	0.73	1.05	2.56
February	0.75	1.09	2.80
March	0.74	1.00	2.26
April	0.76	1.05	2.13
May	0.84	1.03	1.78
June	0.74	0.96	4.10
July	0.77	0.98	2.88
August	0.84	0.96	1.72
September	0.80	1.09	3.14
October	0.74	1.01	2.70
November	0.68	1.05	3.75
December	0.76	1.05	1.91

Table 4.3 Details of monthly adjustments made to reconstructed precipitation. The coefficient of determination (r^2) and Mean Absolute Error (MAE) (mm) are shown for regressions on overlapping years between reconstructed series and the Island of Ireland (IoI) composite series (1900-2000). Also shown are the resultant adjustment factors applied to reconstructed precipitation to derive the Island of Ireland extended (IoIext) series (1765-1849).

4.3.2 Drought events in the IoI series (1850-2015)

Figure 4.2 shows the SPI-12 index for the IoI series (1850-2015). The relative paucity of long droughts in recent years (1980s onwards) is evident, as is a tendency for more intense droughts to occur earlier in the record. In total, 45 individual drought events are identified in the IoI series for the period 1850-2015. Of these, 22 are shorter than 10 months, 19 have durations of between 10 and 20 months, and 4 last longer than 20 months. Figure 4.3 plots drought duration against maximum intensity and mean deficit for all identified events, whilst Table 4.4 presents the top 10 droughts in the IoI series ranked by duration, showing drought start/end dates and drought severity.

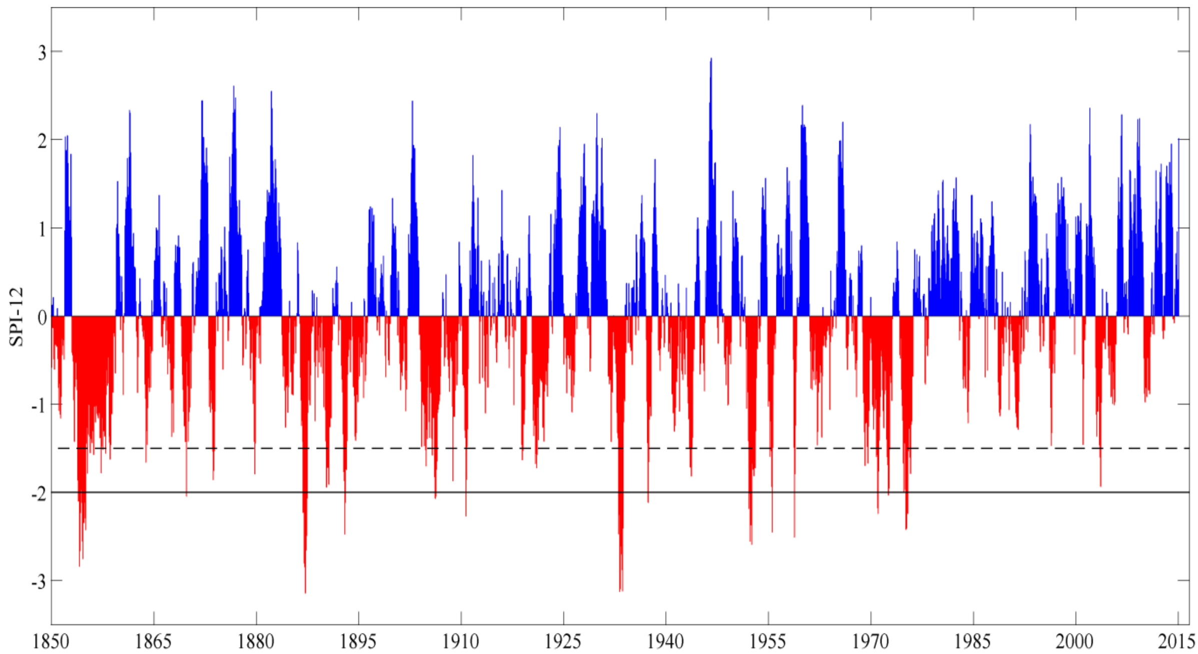


Figure 4.2 SPI-12 series for the Island of Ireland (IoI) composite series 1850-2015. Dashed horizontal line is threshold for severe drought (-1.5) and solid horizontal line is threshold for extreme drought (-2.0).

Rank	Drought Start	Drought Termination	Mean SPI-12	Accumulated Deficit	Drought Duration (Months)	Maximum Intensity
1st	1854-04	1860-05	-1.34	-97.54	73	-2.84
2nd	1905-02	1908-02	-1.15	-41.48	36	-2.07
3rd	1971-02	1974-02	-1.12	-40.47	36	-2.24
4th	1921-06	1923-10	-1.00	-27.86	28	-1.67
5th	1952-09	1954-05	-1.49	-29.74	20	-2.59
6th	1975-06	1977-02	-1.55	-30.98	20	-2.42
7th	1887-07	1889-02	-1.54	-29.29	19	-3.14
8th	1890-10	1892-02	-1.10	-17.64	16	-1.94
9th	1895-05	1896-09	-0.73	-11.72	16	-1.41
10th	1870-04	1871-07	-1.07	-15.99	15	-2.04

Table 4.4 Top ten drought events identified in the Island of Ireland (IoI) composite series (1850-2015) ranked by duration. Also shown are drought start and termination dates together with mean SPI-12, the accumulated deficit and maximum intensity (min. SPI-12 value) recorded during each event.

In the IoI series the longest drought occurred from 1854-1860, persisting for 73 months with maximum intensity of (SPI-12 = -2.82). The most intense drought occurred from 1887-1889 recording a minimum (SPI-12 = -3.14) in February 1888. The most recent drought in the top 10 occurred between June 1975 and February 1977. This event ranked 6th, lasted 20 months and had the largest mean SPI-12 over the period of drought (SPI-12 = -1.55). Figure 4.3 highlights the lack of notable droughts since the 1980s. Variability in drought climatology for the IoI series is further assessed in Figure 4. 4. This plots accumulations of SPI-12 for identified droughts in all 30 year periods from 1881-2015. The relative paucity of prolonged drought events in recent years underlines the value of using long-term data to establish a more comprehensive picture of the drought climatology for the island.

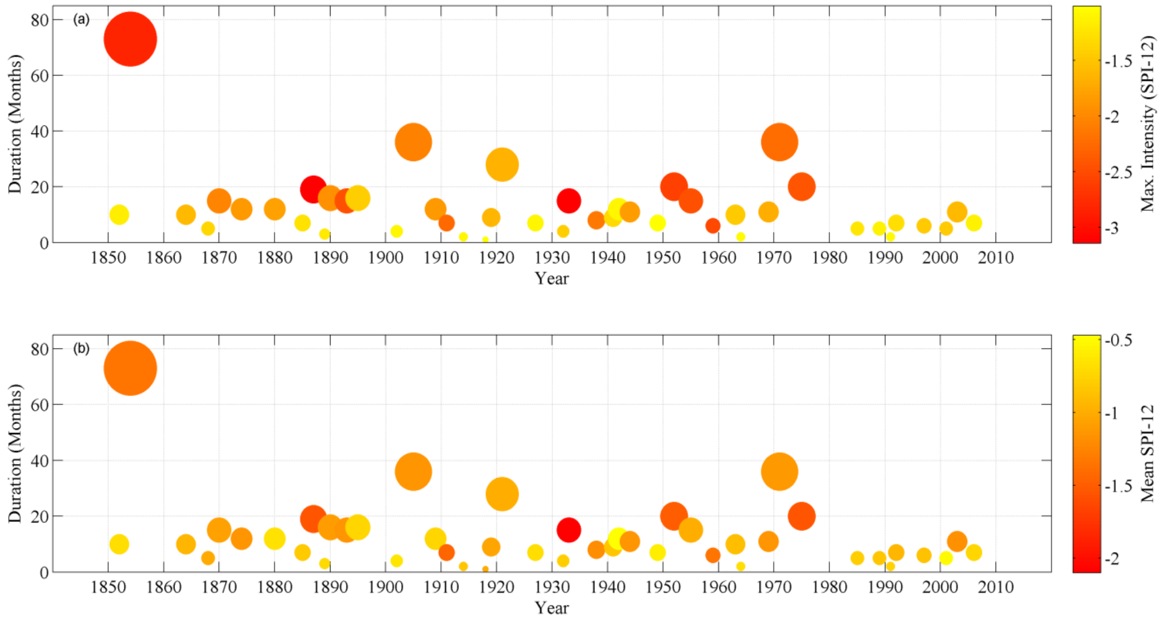


Figure 4.3 Drought duration plotted against a). maximum intensity and b). mean SPI-12 for each of the 45 droughts identified in the Island of Ireland (IoI) series 1850-2015. Circle size denotes duration (months) while the colour ramp indicates intensity and mean SPI-12 respectively.

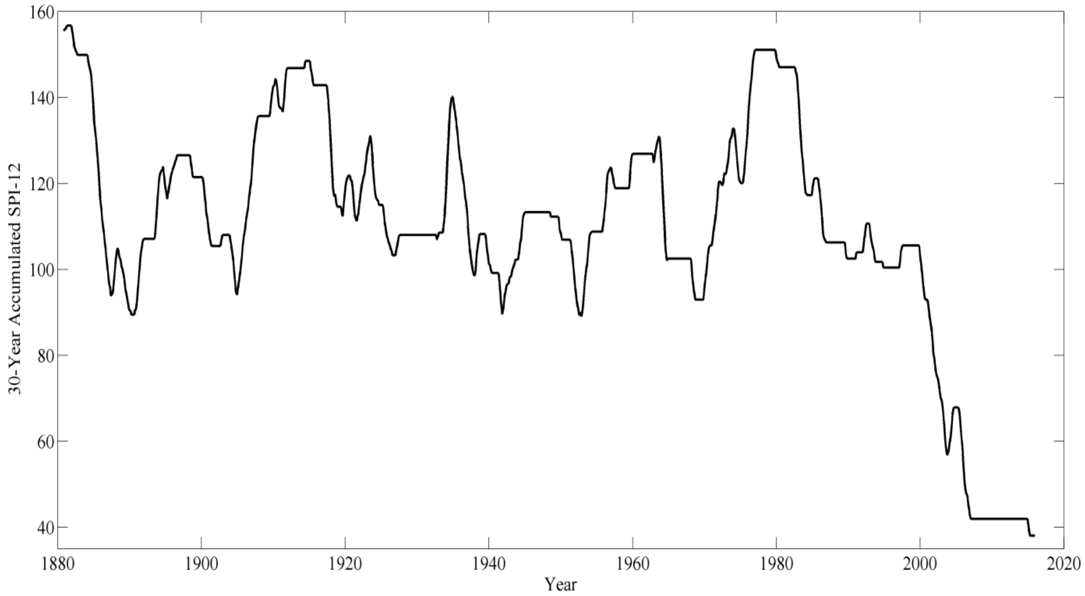


Figure 4.4 30-year accumulated SPI-12 values for identified drought events in the Island of Ireland (IoI) series.

4.3.3 Drought rich periods across the IIP network (1850-2015)

Figure 4.5 shows the SPI-12 matrix plotted for all 25 stations in the IIP network with values colour coded based on drought severity. It is clear that many drought events identified in the IIP series have been island wide in extent. Also evident is the tendency for severe droughts to cluster in time. The relative paucity of droughts in recent decades noted in the IoI series is also seen across individual stations.

A detailed drought catalogue for each of the 25 stations in the IIP network is provided in the appendix (4.1), where all drought events for each station are listed along with information on the duration, the mean, total accumulated and minimum SPI-12 values for each event. See Table 4.5 for example showing the complete detailed drought statistics for IoI series 1850-2015. In the next section attention is focused on understanding the development of drought and attendant socio-economic impacts during drought rich periods in the record. Using the definition of a drought rich period as years in which at least 40% of the stations in the IIP network experience events of at least 18-months duration, the following periods are noted: 1854-1860, 1884-1896, 1904-1912, 1921-1924, 1932-1935, 1952-1954 and 1969-1977.

Figure 4.6 shows the progression and spatial distribution of these events in more detail. Of note is the diversity of drought signatures in terms of their severity and spatio-temporal development. For instance, the events of 1884-1896 and 1969-1977 are marked by intermittent periods of extreme and moderate drought conditions, while the events in 1854-1860, 1932-1935 and 1952-1954 are characterised by prolonged, severe drought conditions. The 'long drought' of 1854-1860 previously identified in the IIP network (Wilby *et al.,* 2015) and UK (Marsh *et al.,* 2007) series is evident. However, in the south and southeast this event appears more intense but of shorter in duration. The drought period of 1921-1924 is the least spatially extensive of those considered, but extreme drought conditions are noted as persisting for a relatively long period at a small number of stations.

Drought Start	Drought termination	Mean SPI-12	Accumulated SPI Deficit	Drought Duration Months	Maximum SPI Intensity
1852-01	1852-11	-0.68	-6.81	10	-1.16
1854-04	1860-05	-1.34	-97.54	73	-2.84
1864-10	1865-08	-0.94	-9.40	10	-1.6
1868-07	1868-12	-1.02	-5.10	5	-1.37
1870-04	1871-07	-1.07	-15.99	15	-2.04
1874-01	1875-01	-1.15	-13.81	12	-1.86
1880-06	1881-06	-0.67	-8.02	12	-1.79
1885-03	1885-10	-0.82	-5.71	7	-1.26
1887-07	1889-02	-1.54	-29.29	19	-3.14
1889-07	1889-10	-0.72	-2.15	3	-1.19
1890-10	1892-02	-1.10	-17.64	16	-1.94
1893-08	1894-11	-1.14	-17.08	15	-2.47
1895-05	1896-09	-0.73	-11.72	16	-1.41
1902-10	1903-02	-0.64	-2.55	4	-1.08
1905-02	1908-02	-1.15	-41.48	36	-2.07
1909-08	1910-08	-0.75	-9.05	12	-1.87
1911-06	1912-01	-1.45	-10.16	7	-2.27
1914-06	1914-08	-0.84	-1.67	2	-1.10
1918-08	1918-09	-1.01	-1.01	1	-1.01
1919-10	1920-07	-1.05	-9.44	9	-1.63
1921-06	1923-10	-1.00	-27.86	28	-1.67
1927-02	1927-09	-0.68	-4.75	7	-1.09
1932-11	1933-03	-0.78	-3.11	4	-1.42
1933-09	1934-12	-2.10	-31.55	15	-3.12
1938-03	1938-11	-1.20	-9.58	8	-2.11
1941-12	1942-09	-0.85	-7.69	9	-1.31
1942-11	1943-11	-0.47	-5.61	12	-1.08
1944-03	1945-02	-1.15	-12.67	11	-1.82
1949-12	1950-07	-0.58	-4.03	7	-1.01
1952-09	1954-05	-1.49	-29.74	20	-2.59
1955-11	1957-02	-0.99	-14.91	15	-2.45
1959-08	1960-02	-1.34	-8.01	6	-2.51
1963-01	1963-11	-0.89	-8.92	10	-1.46
1964-11	1965-01	-0.68	-1.35	2	-1.06
1969-12	1970-11	-1.15	-12.62	11	-1.70
1971-02	1974-02	-1.12	-40.47	36	-2.24
1975-06	1977-02	-1.55	-30.98	20	-2.42
1985-01	1985-06	-0.78	-3.91	5	-1.21
1989-09	1990-02	-0.84	-4.20	5	-1.13
1991-02	1991-04	-0.76	-1.51	2	-1.06
1992-02	1992-09	-0.95	-6.67	7	-1.29
1997-03	1997-09	-0.86	-5.18	6	-1.47
2001-12	2002-05	-0.52	-2.58	5	-1.46
2003-11	2004-10	-1.16	-12.81	11	-1.60
2006-04	2006-11	-0.73	-5.08	7	-1.11

Table 4.5: Island of Ireland (IoI) series (1850-2015);. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified in the IoI series. (1850-2015).

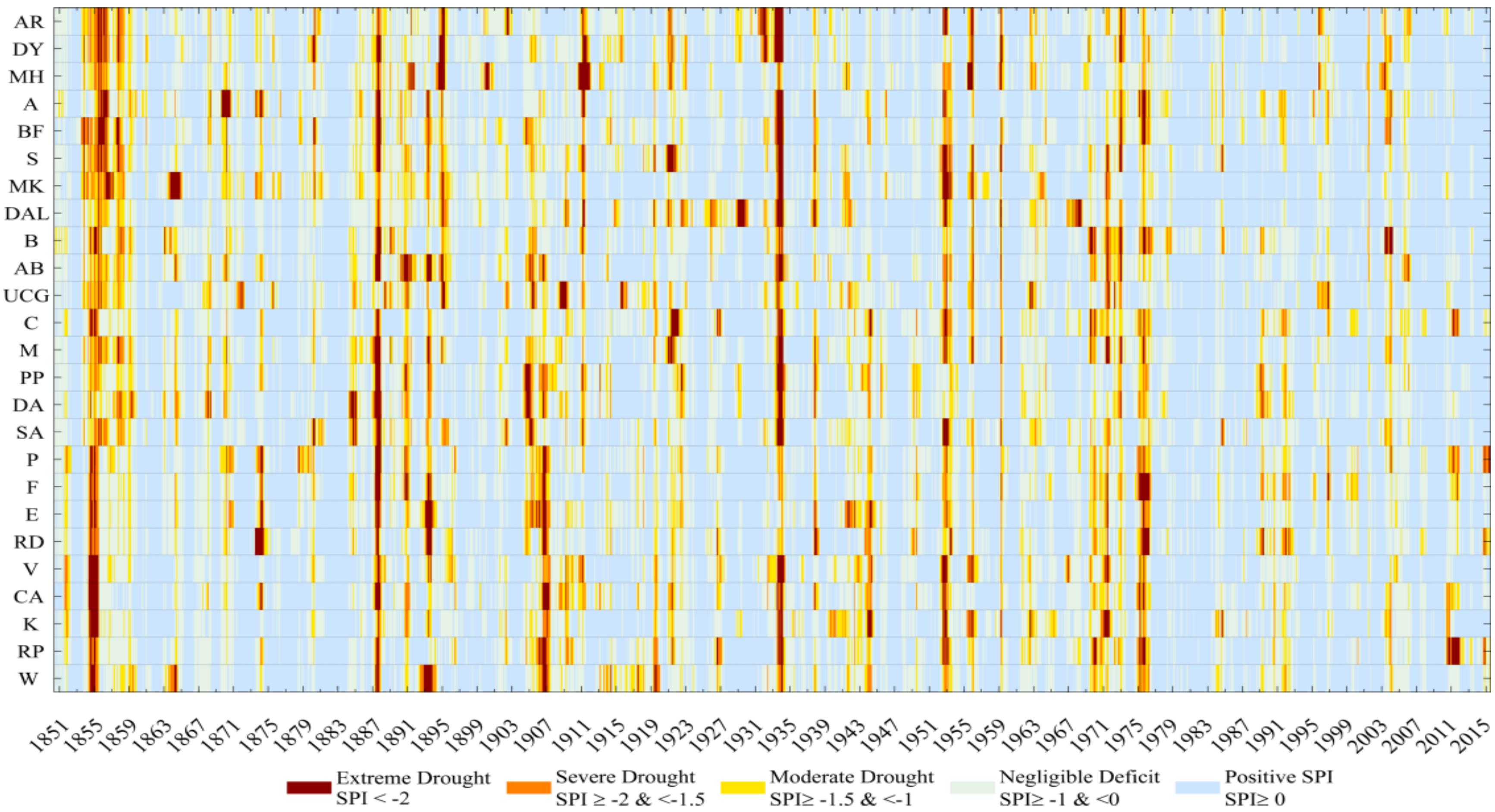


Figure 4.5 SPI-12 values for all 25 stations in the Island of Ireland Precipitation (IIP) network. Negative SPI-12 values are colour coded according to severity thresholds to highlight periods of moderate to extreme drought conditions.

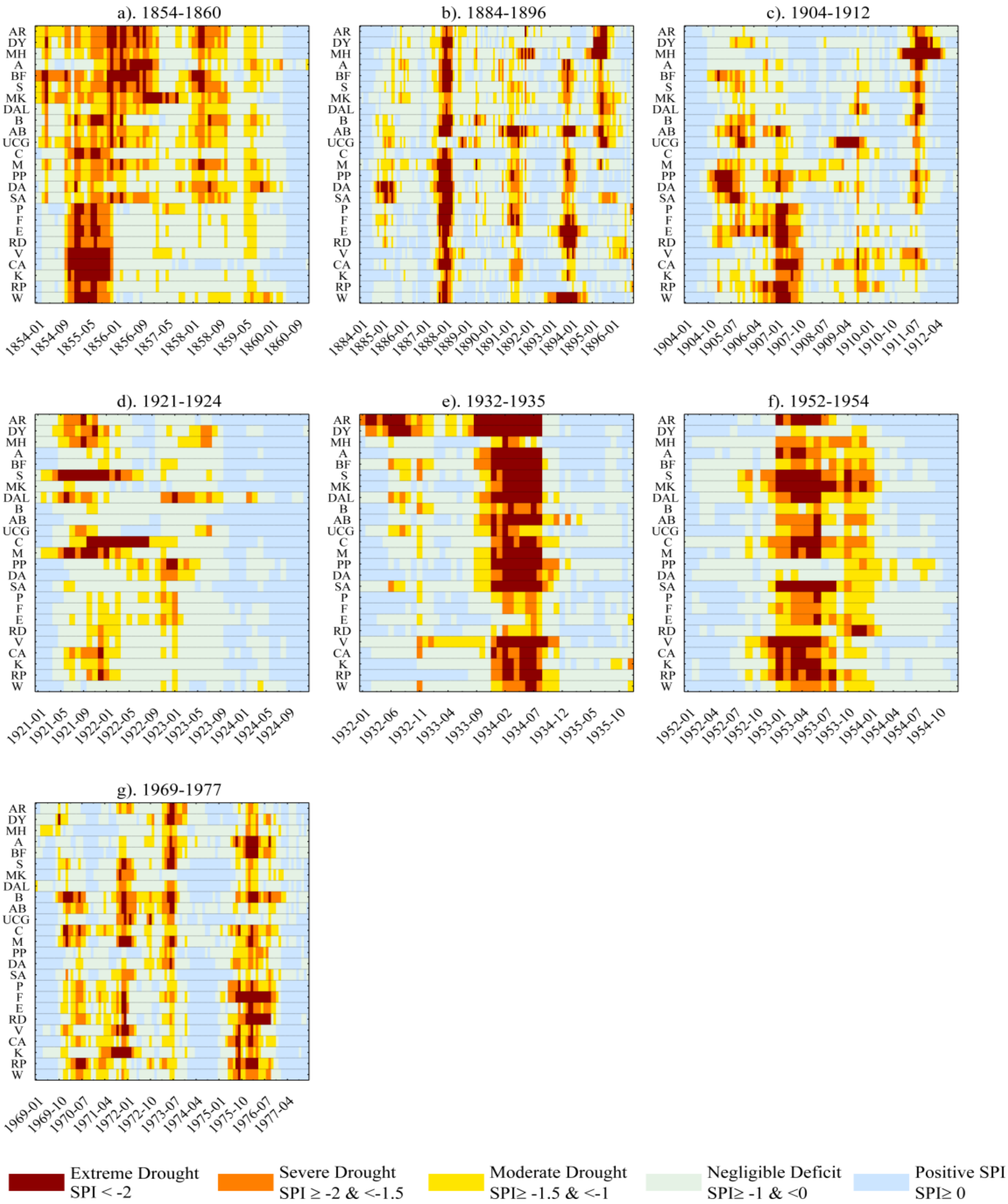


Figure 4.6 Drought signatures showing SPI-12 values for all stations in the Island of Ireland Precipitation (IIP) network for the 7 drought periods identified with island wide impact. Negative SPI-12 values are colour coded according to severity thresholds to highlight periods of moderate to extreme drought conditions.

In the following sections each of the drought rich periods identified above are further analysed and their development and impacts are traced with reference to documentary evidence using the sources outlined in section 4.2.5. Note that when tracing the evolution of each drought, the date of publication of newspaper articles is also provided.

1854-1860

This drought began in December 1853 in the northeast, spreading to western and northern regions by January 1854. It extended south to Shannon Airport by April 1854. Drought reached other parts of the south and southeast around September 1854. In all regions drought persisted until April/May 1860, lasting more than 70 months at 16 stations in the IIP network. The drought was most intense in the south and southeast with minimum SPI-12 values for Valentia (-3.99), Cork (-3.83), Killarney (-3.14) and Waterford (-2.87) recorded between January and April 1855. Despite being most intense, events were relatively less protracted in these areas.

There are references to drought commencement in several newspapers (AC, 27.04.1854, page 2; FJ, 27.05.1854, page 4). The *Freeman's Journal* notes the increasing cost of agricultural produce at Dublin Market with a lack of fodder and unusually late potato and wheat crops (FJ, 04.05.1855, page 4). The *Irish Examiner* reports that the soil was very absorbent with rainfall being soaked up by the parched earth (IE, 07.06.1854, page 4). Due to the scarcity of pasture many cows remained dry of milk and unsold at the Dublin market, with similar conditions and falling prices experienced at other monthly fairs across the island (IE, 07.06.1854, page 4).

Some respite came with rainfall across specific regions in summer 1854. Whilst some crops recovered in time for harvesting, rainfall was not sufficient to relieve drought conditions (N, 08.07.1854, page 14). Later in the drought there are also accounts of sporadic wet weather. However, there are also references to rain events that made the land unfit for yielding crops due to the soil damage caused by the preceding drought (IE, 30.05.1859, page 2; TC, 21.06.1859, page 2; BN, 31.05.1859, page 4; BN, 01.06.1859, page 2). The summer of 1859 saw severe water shortages for Dublin City. Restrictions by order of Dublin City Hall were in place on both domestic and manufacturing water usage as well as a complete ban on watering the streets (FJ, 11.07.1859, page 1). By early 1860 agriculture was in a "distressing condition" with crop failures, rotted wheat and livestock suffering from a lack of grass (FJ, 10.07.1860, page 2). By May and early June 1860 rainfall returned and, although wells were dry and groundwater supplies depleted, heavy continuous rainfall replenished stocks to a satisfactory state (FJ, 16.05.1860, page 4; FJ, 02.06.1860, page 3; FJ, 10.07.1860, page 2; FJ, 15.07.1806, page 2).

1884-1896

The period 1884-1896 saw severe multi-year droughts punctuated by periods of positive SPI values. Evidence indicates that the most intense and widespread drought in the period 1850-2015 occurred in 1887. This event began between May and June 1887 along the east coast and spread island-wide, with a drought duration at most stations greater than 30 months and longest at Strokestown lasting 60 months. Maximum intensity was experienced at Dublin (-3.54) while the largest accumulated deficit was experienced at Ardara (-105.02).

Barrington (1888) described widespread crop failures across Ireland in 1887 with barley, oats, and potatoes stocks severely depleted. However, it appears conditions suited the wheat crop in the northeast and southeast. The 1887 drought caused widespread crop failures, reduced vegetable growth and livestock losses in Clare, Tipperary, Wexford, Antrim, Galway, Kerry and Dublin (N, 15.10.1887, page 11; IT, 26.06.1887, page 3; IT, 02.07.1887, page 5; IT, 06.07.1887, page 5; IT, 08.07.1887, page 6; IT, 03.09.1887, page 7). Drought also impacted the linen trade in the north with factories closed due to lack of water-power (IE, 25.08.1887, page 4). In August 1887, low water pressure in Dublin caused problems when responding to fire in the city centre (IT, 09.08.1887, page 4). Reductions in tram receipts were attributed to excess dust caused by the drought (IT, 31.08.1887, page 3). Sewerage systems were reported blocked due to lack of water, leading to public health concerns (IT, 30.06.1887, page 6; IT, 21.07.1887, page 5).

Extreme drought returned in spring 1893 across the south, east and southeast. Waterford, Rathdrum and Enniscorthy stations show drought conditions lasting until July/August 1896 with peak SPI12 intensities below -3.00. The west, northwest and some midland stations experienced less severe deficits with drought terminating earlier. The 1893 drought depleted water levels in the Vartry reservoir, Dublin's major water source (FJ, 14.03.1894, page 7), with water leakages from a degraded distribution network deemed to have exacerbated the public water supply situation. The event saw demands for a repair and monitoring programme and debate over potential new water sources for the city (IT, 23.11.1893, page 6; FJ, 14.03.1894, page 7).

1904-1912

The drought began in October 1904 in the east and northeast and was evident in all stations by June 1905. Drought duration varied from 10 months at Armagh to 64 months at Dublin. The peak severity (-3.03) at Cork in the south was recorded in March 1907. Regions worst affected were in the south, east and some areas of the southwest. This period of drought was episodic, punctuated by intermittent rainfall events. Levels in the inland navigation canal and Royal canal fell to an extent that reduced their navigability (II, 08.09.1911, page 4). The reservoir located in the midlands at Longford dried up completely (II, 08.09.1911, page 4). By June 1912 most areas were back to near normal conditions except for Ardara and Malin Head where drought persisted until December 1912.

1921-1924

This severe two year drought began in February 1921 across the midlands and west regions. However, by summer 1921 all areas were affected. Strokestown recorded the greatest peak intensity (-3.56) in October 1921. In the east the drought peaked several months later in January 1923 but was less severe (-2.25) at Phoenix Park. Drought duration varied between 11 to 32 months, causing widespread water restrictions (II, 20.06.1921, page 4). There were also concerns that the Vartry reservoir would dry up completely, with comparisons made to the 'Great Drought' of 1893 (II, 20.06.1921, page 4).

1932-1935

The first signs of drought appeared at Ardara and Valentia in October 1931, Derry in February 1932, spreading to the other stations in the south/southwest by summer/autumn and the rest of the island by autumn 1933. The greatest intensity was experienced at Derry (-4.38) and Ardara (-3.79); with the drought also of longest duration at the latter (69 months) [but note potential issues found in the metadata around 1931 for Ardara in Noone et al. (2015)]. At 12 stations the drought lasted longer than 25 months, terminating at most stations by November 1934. Farmers in Wexford experienced water shortages with ponds, springs, wells and streams drying up (IE, 25.07.1934, page 5). Milk and butter yields were well below normal and beet and turnips crops failed (IE, 25.07.1934, page 5). Low reservoir levels in Enniskillen in the north impacted flax growers and in Clonmel (in the south) residents were asked to stop watering gardens unnecessarily (IP, 08.08.1935, page 1).

1952-1954

The onset of another severe two year drought began in November/December 1952 and persisted in most areas until August/September 1954. Stations in the west, midlands, northwest and south were severely affected, with Shannon recording the greatest intensity (-3.41; June 1953). Drought duration ranged from 12 months at Derry to 24 months at Portlaw. Newspaper reports state that milk yields were diminished, rivers and lakes were well below normal levels and tillage growth was reduced due to hard ground (II, 27.03.1953, page 2; NG, 14.02.1953, page 5). Hydroelectric output was also well below average (LL, 10.10.1953, page 9).During 1952/3 there were also reports of a marked reduction in the quantity of salmon, oysters and eels due to an insufficient flow of water in the weirs located at Castleconnell and Thomond, County Limerick (Electricity Supply Board,1953; LL, 10.10.1953, page 9)

1969-1977

This period is marked by a clustering of drought events. The first began across most stations in October 1969 and terminated in August 1970 across northwest, northeast and west regions. The midlands, south and southeast were more severely affected with Birr recording a peak drought intensity of -2.86 in January 1970. Drought returned to most stations by autumn 1971 with greatest intensity at Killarney (-2.99) in September 1971. Drought duration of 53 months is recorded at Belfast. The event terminated in December 1973 at most stations but persistent drought conditions returned to all stations by August 1975. The southeast, south and northeast were severely affected. Armagh recorded the lowest SPI-12 value (-3.05) in January 1976 with SPI-12 values persistently below -2.00 for several months. Most stations located in the midlands, south and southeast recorded persistent SPI-12 values of this magnitude for more than 4 months during the summer of 1976. All stations returned to near normal conditions by August 1977. Drought impacts included reduced levels in reservoirs supplying water to Dublin City, provoking stringent water restrictions (O' Laoghog, 1979). Water supplies were stressed in 1976 due to increased demand during the previous summer and insufficient replenishment during the intervening dry winter (O' Laoghog, 1979). The severe lack of water for livestock and the poor condition of crop and grazing lands affected agriculture (WP, 19.07.1975, page 22).

4.3.4 Reconstructed drought events 1765-1849

For the period of reconstructed rainfall (1765-1849) Figure 4.7 plots SPI-12 for the IoIext series. Of note is the lack of drought in the early record (~1766 to 1775). In total 23 droughts are identified throughout the reconstructed period, 7 of which are shorter events lasting less than 10 months. Figure 4.8 plots duration of all droughts in the IoIext against their maximum intensity and mean SPI-12. Evident is the long, intense event around 1800-1804 (49 months), followed closely by two shorter but also intense events in 1805-1806 (23 months) and 1807-1809 (22 months). These three droughts are only briefly punctuated by near normal conditions and are treated as continuous drought periods below.

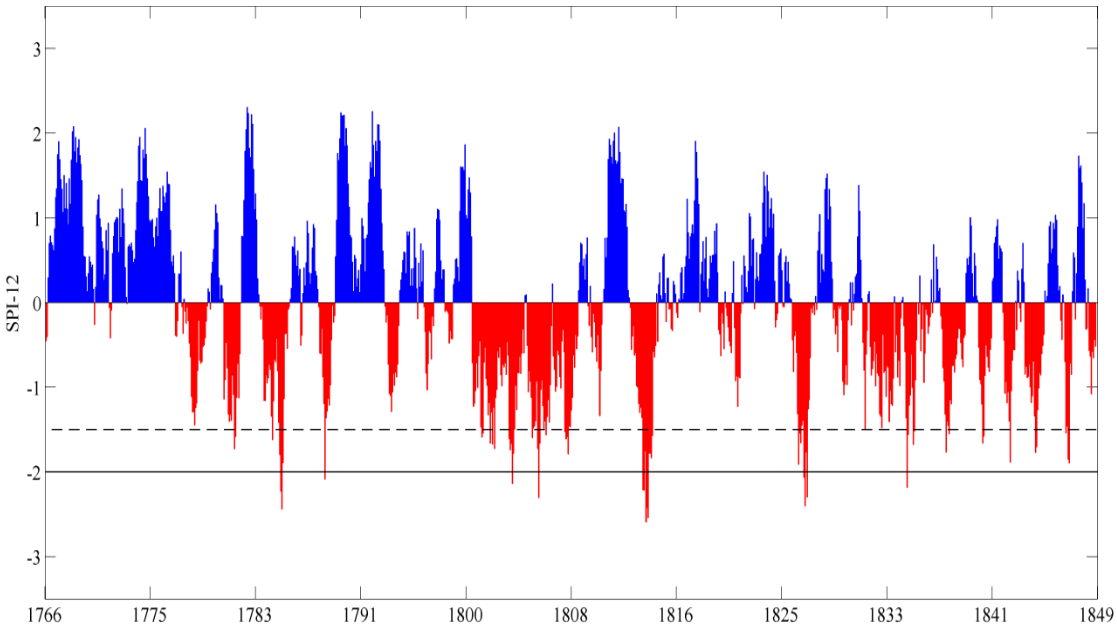


Figure 4.7 SPI-12 series for the Island of Ireland extended (IoIext) series 1765-1849. Dashed horizontal line is threshold for severe drought (-1.5) and solid horizontal line is threshold for extreme drought (-2.0).

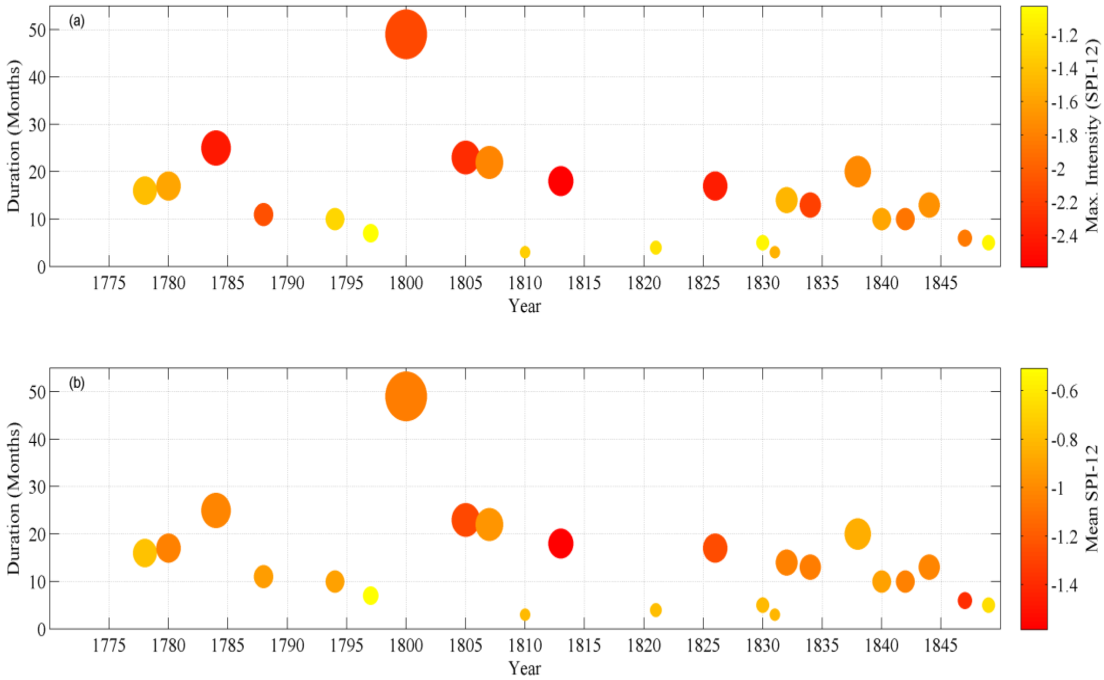


Figure 4.8 Drought duration plotted against a). maximum intensity and b). mean SPI-12 for each of the 23 droughts identified in the Island of Ireland extended (IoIext) series 1765-1849. Circle size denotes duration (months) while the colour ramp indicates intensity and mean SPI-12 respectively.

Shorter, but particularly intense droughts are noted in 1813-1815 (18 months), 1826-27 (17 months) and 1838-1839 (20 months). The latter occurs within a cluster of events from approximately 1830 to 1849, which tend to be relatively brief but intense events. It is also notable that the Great Irish Famine of 1845-1852 occurred during this period of intermittent drought. The following sections provide an overview of key impacts for long drought events in this IoIext series. Although the 1826-27 drought event lasted for 17 months, this event is included below because it coincided with the famine of 1826. Table 4.6 gives statistical details on each drought and an overview of the accompanying documentary evidence.

Year	Duration months	Summary of Socio-economic impacts	Sources
1784-1786	**25**	Rivers and lakes in England completely dried up, livestock died. Ireland 1785 "remarkable heat and drought". Linen mills could not work due to lack of river flow. A temporary embargo was placed on Irish distilling and on grain exports. Famine occurred with diseases such as "fever, dysentery, scarlatina, ophthalmia, and influenza" all rife.	Garnier,et al (2015) Symons, (1887) Ó Gráda, (2015)
1800-1804	**49**	The woollen industry declined in 1802 due to lack of water to work the mills. 1800 and 1801 summer temperatures "very hot" rarely experienced before. June 1803 Ireland was "nearly burned by drought". Springs and rivers completely dried up. Potato crop failures, the main food source at this time causing severe hardship. 1799-1801 famine with potato crops extremely scarce.	FJ,09.09.1800, page 3 FJ,15.07.1806, page 2 Census,(1851);Whistlecraft, (1851) Kelly, (1992);Garnier *et al.*, *(*2015)
1805-1806	**23**	The drought which had prevailed in England gave farmers such serious alarm.	FJ, 15.06.1805, page 2
1807-1809	**22**	Defective crops and produce falling short of usual yields due to drought. After several weeks of intolerable heat and great drought the earth has been refreshed with rain showers.	BF,11.08.1807, page 2 FJ,28.07.1807, page 2
1813-1815	**18**	June, July and August 1815 very hot with exceptionally mild winter. In England many ponds and rivers dried up.Grass became very scarce. Drought preceded the Irish famine of 1816-1818 when 40-60,000 Irish people lost their lives.	Census, (1851) Symons, (1887) Kelly,(1992);ÓGráda, (2015)
1826-1827	**17**	Reports that not a shower of rain had fallen since the 27th May 1826. Temperatures reached 115º Fahrenheit on Sunday 25th June. Ireland 1826 "not a breath of air stirs" and no clouds could be seen in the sky. Ireland 1826 continued to experience very hot temperatures and excessive drought. The summer of 1826 had not occurred in the living memory of the oldest man. Irish farmers named this as "the year of short oats". Crops in a poor state, wool production reduced and hop growth depleted.	FJ,28.06.1826, page 4 BN,22.08.1826, page 2 BN,06.07.1827, page 2 Census, (1851); Symon's (1887) Mc Sweeny,(1831)
1838-1839	**20**	Dry scorching wind, Ireland was experiencing severe weather and the sun has been very strong. Lack of upland crop growth, with flax seed growing but not a very healthy crop. Famine in Ireland during 1839 with high prices of potatoes but little excess mortality	FJ, 06.06.1839, page 4 Ó Gráda, (2015)

Table 4.6 Details of the 7 drought events identified for analysis from the Island of Ireland extended (IoIext) series (1765-1849). Also presented is the duration of each event (months) together with associated documentary evidence.

1784-1786

The drought of 1784-1786 lasted 25 months with an accumulated deficit of -25.61 reaching maximum intensity (-2.43) in July 1785. Newspaper articles refer to extreme drought throughout Europe, England and southern parts of Ireland in 1785 (BN, 20.06.1788, page 3; BN, 22.07.1785, page 2; FJ, 03.09.1785, page 3). Symons (1887) also notes that 1785 was a year that experienced "remarkable heat and drought", whilst Garnier *et al.,* (2015) mention reduced productivity in textile and flour industries due to water shortage. Ó Gráda (2015) makes reference to the drought of 1784-1786 and subsequent famine, noting that disease was rife and a temporary embargo was placed on distilling and grain exports.

1800-1809

The sequence of droughts between 1800 and 1809 was the most remarkable in the entire 250-year record analysed. The first drought began in September 1800 and lasted 49 months until October 1804 - with an accumulated deficit of -51.33 and maximum intensity (-2.13; October 1803). Following a three-month respite, the second drought phase commenced in January 1805 and lasted 23 months until December 1806, with an accumulated deficit of -29.24 and maximum intensity (-2.30) in November 1805. After another three months of near normal SPI-12 values, the third drought phase began in March 1807, lasted 22 months until January 1809, recording an accumulated deficit of -21.02 and maximum intensity of (-1.78) in March 1808.

There is evidence that, at least early stages of the event, drought effects were not island-wide with counties Leitrim and Roscommon producing potatoes and other crops for supply to severely impacted areas in the south and west (FJ,03.01.1801, page 2). In 1802, Irish officials put in place financial support to import maize from the United States to alleviate the emergency (Ó Gráda, 2015). There are also a number of references to this period in the 1851 Census, which notes that summer of 1800 was unusually hot and dry, and in the period June-September 1803 Ireland was "nearly burned by drought", with springs and rivulets drying up (Census, 1851). There is also evidence of this being a severe drought period across the UK and Europe with reports of poor crop growth and livestock dying (IT, 09.01.1801, page 2; IT, 06.02.1802, page 5; FJ, 18.01.1803, page 2; FJ, 15.06.1805, page 2).

1813-1815

Within the IoIext series this event lasts 18 months (September 1813 to March 1815) with an accumulated deficit of -28.53 and maximum intensity (-2.59) in May 1814. The 1851 Census reports that June, July and August 1815 were very hot and winter 1815 very mild, although there is no reference to rainfall. This event is also noted in England where Symons (1887) mentions that many ponds and rivers dried up and grass became very scarce. The *Freeman's Journal* reports that in October 1814 the drought had increased corn and wheat prices forcing brewers to use alternative ingredients, sometimes with poisonous consequences (FJ, 15.10.1814, page 3). This intense drought immediately precedes the Irish famine of 1816-1818 when 40,000 to 60,000 Irish people lost their lives (Kelly, 1992; Ó Gráda, 2015). The infamous year 1816 'without a summer' followed the catastrophic volcanic eruption and global cooling of Tambora in April 1815 (Raible *et al.*, 2016).

1826-1827

Commencing in May 1826 and terminating in September 1827 (17 months) this was a severe drought with SPI-12 values less than -1.50 for 7 consecutive months coinciding with the famine of 1826, causing severe hardship to the population (Mc Sweeny, 1831; Ó Gráda, 2015). The drought reached a maximum intensity (-2.40) in December 1826. Linen Hall, Belfast is reported as having very low rainfall throughout the summer of 1826 (Barrington, 1888). Farmers were forced into an early harvest. However, due to the severe drought, early potato crops failed, pastures suffered severely and cattle prices were very low (IT,11.07.1826, page 3; BN, 22.08.1826, page 2).

1838-1839

This is the most persistent drought phase within the cluster of events that occurred between 1830 and 1849. The drought began in January 1838 and terminated 20 months later in September 1839, reaching an accumulated deficit of -17.18 and maximum intensity (-1.76) in February 1838. There are reports that both flour and oatmeal arrived slowly to markets due to drought in 1838 (LE, 20.10.1838, page 4). In the southeast farmers told of soil that was so dry it was difficult to cultivate and that both the tillage and growth of the potato crop was delayed in 1839 (FJ, 21.05.1839, page 2; FJ, 04.06.1839, page 4). In June 1839, the *Freeman's Journal* notes that in many parts plants were parched, vegetation had made little growth and the drought was so severe that the ground was difficult to work (FJ, 06.06.1839, page 4). In 1839, Ireland experienced a famine with potatoes at a very high price causing hardship but relatively small increases in mortality (Ó Gráda, 2015).

4.4 Chapter Discussion

The assessment of drought occurrence and impacts presented here yields new insights into the experience of drought in Ireland. The IoI (1850-2015) and IoIext (1765-1849) series reveal 68 individual drought events over the last 250 years. Fourteen long duration droughts (>18 months) are identified, with seven occurring in both the IoI (see Table 4.4) and IoIext (see Table 4.5) series. Impacts from severe drought periods include reduced or failed crop yields, increased crop and dairy prices, human and livestock health issues, water restrictions, low reservoir levels, water supply failures and hydro-power reductions. During the period 1765-1849 many long duration events occur during or immediately prior to famine events in 1782-1784, 1800-1801, 1816-1818, 1839 and 1845-1849 (Great Irish Famine) (Ó Gráda, 2015). Across the analysis, two long duration events are particularly noteworthy: the drought of 1800-1809 (in fact a series of three droughts with brief three month interludes) and the continuous event of 1851-1860 (73 months). In the absence of brief reprieves the 1800-1809 period might plausibly have resulted in 100 months of continuous drought as defined by the criteria.

It has to be noted that some of the drought events identified in the reconstructed series for the period 1765-1849 may have been underestimated due to issues of low variability. The Casty (2007) precipitation series was reconstructed using available long-term observations, documentary evidence and natural proxies such as tree-rings, ice cores, corals and speleothem. There is a marked difference in the variance of the data for the period 1765-1849 when compared to the 1850-2015 series, which is more than likely due to the proxy evidence not capturing the full extent of the variance. Hence, this chapter conducted the analysis on the two data periods; observation series 1850-2015 and reconstructed series 1765-1849. Future work could investigate using statistical methods to compare the ratio of the two variances between the observations and the reconstructed series, once completed a variance inflation step could be implemented on the reconstructed series.

A key insight gained is the relative paucity of droughts in recent decades, particularly since the 1980s. Although occasional intense drought events have occurred in this period (e.g. 1995, 2006, 2013) these have been relatively short-lived. Thus, in comprehensively characterizing drought climatology the study demonstrates the added-value of long records. This assessment of drought accumulations over continuous 30-year periods for the IoI series (1850-2015) highlights the unusualness of the recent record and how unrepresentative the period since 1980 is of the long-term drought climatology of the island. The large decline in accumulated SPI-12 values around the 1990s (Figure 4.4) is consistent in timing with the regime shift in Atlantic Ocean influence on European climate identified by Sutton and Dong (2012). It also has to be noted that three of the top ten wettest summers in the IoI series since 1850 have occurred since 2000 (2007; 2008; 2009) (Noone *et al*., 2015). Matthews *et al.,* (2015) note an increase in storminess in summer in recent decades and Wilby *et al*., (2015) highlight that the probability of a dry half-year followed by another dry half-year is currently lowest since 1850.

Assessment of drought across the 25 stations in the IIP network (1850-2015) shows general coherence with findings from the IoI series. This study identified seven drought rich periods across the island in 1854-1860, 1884-1896, 1904-1912, 1921-1924, 1932-1935, 1952-1954 and 1969-1977. However, this chapter assessment reveals substantial variations in terms of drought development, severity, and spatial extent across the network as a whole (see Figure 4.6). For instance, 1884-1896 is characterised by spatially uniform clusters of extreme drought events, while 1854-1860 is marked by protracted drought conditions with the event being markedly shorter and more severe in the southeast. Drought in the period 1921-1924 is the least spatially coherent. Such diversity questions the practice of using single events for tasks such as drought planning. Uncovering the climatological drivers of drought rich periods (e.g. Moreira *et al*., 2015) would facilitate a deeper understanding of past events. Such knowledge is critical for establishing how climate variability and change might influence future drought occurrence.

The drought catalogue draws extensively on documentary sources, particularly newspaper records, digitised, and made searchable by the Irish Newspaper Archive. Such sources contain some of the longest running publications in the world and offer unique insights into the socio-economic impacts of drought. This chapter shows that such archives can be used to trace evolving drought situations and their impacts. These independent sources also increase confidence in the quantitative findings of drought indicators, particularly for droughts falling in the period prior to available digitised records (typically 1940 in Ireland) or the reconstructed IoIext series. This chapter advocates for wider use of newspapers in understanding the impacts and climatology of historic droughts, and note the many references to UK drought within the early Irish print media. Murphy *et al*., (2016) further elaborate on insights offered by the documentary archive compiled here.

Given that evaporative losses can exacerbate summer drought it would be preferable to use a drought indicator that incorporates this variable (e.g. Standardized Precipitation-Evaporative Index; Vicente-Serrano *et al*., 2010). However, long-term, quality assured series of evaporation or temperature are not yet available for the island of Ireland. Work is ongoing to derive a temperature series by transcribing and homogenising archived records. This will facilitate assessment of shorter droughts (e.g. SPI-3) and reconstruction of river flows to examine hydrological drought (as in Jones et al., 2006). It must be noted that false positives were not searched – that is droughts in documentary sources that are not detected by the IoIext reconstruction. Pre-1850 droughts are based on reconstructed data and thus findings must remain tentative. However, corroboration of the identified events by documentary evidence from various sources increases confidence. Moreover, throughout the 250 years analysed there are many similarities with drought periods identified in neighbouring regions of the UK during such as 1800-1809, 1826 and 1833-3 (e.g. Todd *et al*., 2013; Marsh *et al*., 2007; Cole and Marsh 2006).

Finally, these findings have significant implications for future infrastructure and water resource planning plus resilience assessment of critical services under severe drought conditions. When advising Irish local authorities developing climate change adaptation strategies, Gray (2016) recommends adopting a 30-year window as appropriate to identify weather extremes and climatic trends in assessing resilience to climate variability. This work clearly shows that where vulnerability to drought is an issue, such guidance would result in considerable maladaptation with potentially serious consequences. The combination of droughts of various duration, evolution and intensity identified here provide a diverse set of conditions under which to stress-test current and planned infrastructure, particularly in the water sector (e.g. Spraggs *et al.*, 2015; Watts et al., 2012). To this end, detailed information on all droughts (duration, mean intensity, accumulated deficits and maximum intensity) identified for each of the 25 IIP network stations (1850-2015) is provided as Supplementary Information (Appendix 4.1). Practitioners can identify the most suitable event or combination of historical events for the purpose at hand.

4.5 Chapter Conclusion

This chapter has developed a 250-year drought catalogue for Ireland. Employing the Standardised Precipitation Index (SPI) to identify droughts across 25 stations in the Island of Ireland Precipitation (IIP) network, (IoI) and (IoIext) series the results show that the region is surprisingly drought prone. During the period 1850-2015, seven major drought rich episodes are identified that impact simultaneously at least 40% of the study sites in 1854-1860, 1884-1896, 1904-1912, 1921-1924, 1932-1935, 1952-1954 and 1969-1977. The detailed analysis of SPI metrics highlights the substantial diversity of events in terms of drought development, severity and spatial extent across the island. Extension of this analysis to 1765 revealed a further seven persistent drought episodes, of particular note being the period 1800-1809. Extensive integration of documentary sources from newspaper archives increases confidence in the droughts identified across the 250 years of record. The work shows that value-added by combining qualitative and quantitative evidence of former droughts to arrive at a more coherent understanding of their development and historic impacts.

The most important finding of this chapter is that recent decades are not representative of the long-term drought climatology of Ireland. Hence, there is a danger that infrastructure and water resource plans benchmarked against the 1995 drought may underestimate the potential supply deficits that could occur with a return to conditions experienced in the 18th and 19th Century. Further research is needed to improve understanding of the ocean-atmosphere drivers associated with eras of more persistent drought in Ireland. Past severe droughts can also be used to stress-test the resilience of planned water resource developments, at least to the climate variability experienced over the last 250 years.

This chapter has addressed **thesis objective 4** by producing a 250-year drought catalogue for the Island of Ireland. The next chapter will use the IIP precipitation records to reconstruct river flow records at selected Irish catchments for the period 1850-2015. The reconstructed river flows will be analysed using indices to identify historical hydrological drought. Chapter 5 will address **thesis objective 5.**

5 Reconstruction of Irish river flows and identification of drought 1850-2015

5.1 Introduction

The main driver of river flow is precipitation and any changes in this variable will impact on water supply and quality. However, long hydrological records are crucial to detect changes as analyses over short records can result in conflicting results when compared to the longer term (IPCC, 2014; Noone *et al.,* 2015). Longer records also reveal important insights into past hydrological events while contextualising recent extremes (Jones & Lister, 1998; Jones *et al*., 2006; Wilby *et al.,* 2006; Noone *et al.,* 2015: Spraggs *et al.,* 2015; Noone *et al.,* 2016). It is often difficult to find long hydrological records with most hydrometric gauges only starting in the 1950s and 1970s (Jones *et al.,* 2006; Spraggs *et al.,* 2015; Murphy *et al.,* 2012). In Ireland, the commencement of river flow monitoring typically coincides with the onset of arterial drainage in the 1940s/1950s and the occurrence of low flows in the mid-1970s when local authorities became concerned about ensuring adequate supply to meet demand (Murphy *et al.,* 2013). Issues of unnatural flow regimes and commencement of monitoring during the most severe drought of the last forty years therefore confounds the analysis of variability and change in river flow records.

In addressing the lack of long hydrological records previous research has employed reconstruction techniques. Jones (1984) used the statistical relationship between long UK precipitation records and observed river flows to produce monthly river flow records to 1860. The study used an empirical catchment model to reconstruct river flow at 10 catchments at both upland and lowland locations, noting that it was possible to use as little as four rain gauges in deriving catchment rainfall (Jones, 1984). These reconstructed records allow for the effects of climate change on river flow and past extreme events to be assessed (Jones, 1984). This work was subsequently updated by Jones *et al.* (1998) and Jones *et al.* (2006) with both studies focussing on the assessment of historical drought and low flow events. Watts *et al.* (2015) assessed the resilience of water company drought plans using the reconstructed river flows originally produced by Jones *et al.* (2006) and Wade *et al.* (2006) at two rivers the Exe and Ely Ouse. The study noted that the long severe droughts of the 19th century are particularly useful for testing current and future water supply systems and provide a baseline for adaptation planning (Watts *et al.,* 2015).

Other studies have also attempted to reconstruct long river flow records for drought analysis. Spraggs *et al.,* (2015) reconstructed historical drought for the Anglian Region (UK) by employing long rainfall series and extended potential evapotranspiration (PET) data. The data was used to force rainfall runoff models to simulate river flow (1798-2010) and to subsequently simulate reservoir levels for drought assessment (Spraggs *et al.,* 2015). The results highlight periods of prolonged drought with the most severe events occurring between 1854-1860 and 1893-1907 (Spraggs *et al.,* 2015). Lennard *et al.,* (2015) reconstructed river flows (1882-2012) for the Severn Trent water supply region in the UK and examined the implications of historical drought on water supply yield calculations. The study used precipitation and PET data to run the hydrological model HYSIM (Lennard *et al.*, 2015). The study identified several notable drought periods in the reconstructed flow series; 1887-1889, 1892-1897, 1921-1923, 1933-1935, 1975-1977 and 1995-1998 (Lennard *et al.*, 2015). Each of these studies highlights the utility of long-term reconstructed river flows to water planning and to understanding variability and change in catchment hydrology.

In Ireland the hydrometric network consists of over 800 gauging stations; however the temporal coverage is sparse. The majority of gauges were only set up in the mid 1970s to monitor low flows which became problematic at the time, with only a small number of gauges with records starting in the 1950s (Murphy *et al.,* 2013). The Irish Reference Network (IRN) consists of 43 river flow gauge locations across the Island of Ireland identified as suitable for ongoing monitoring and detection of climate driven changes in river flows (Murphy *et al.,* 2013). The criteria for selection of IRN catchments include the amount of basin development, absence of river regulation, record length, station longevity, data accuracy and quality (Murphy *et al.,* 2013). Therefore, the IRN river flow gauges have good consistent hydrometric data quality, near natural flow regimes and a minimum of 25 years of record. In addition, IRN catchments are representative of Irish hydrological conditions (Murphy *et al.,* 2013). Assessment of observations from this network has found strong positive trends in high flow indictors with trends in summer (increasing) and winter (decreasing) mean flows were not as would be expected with climate change and likely an artefact of record length (Murphy *et al.,* 2013).

There is now a clear opportunity for reconstructing long term Irish river flows using the newly created IIP records 1850-2015 (Noone *et al.,* 2016). Therefore, this chapter aims to undertake this task for selected Irish catchments from the IRN and identify and analyse the river flow for drought, thus addressing **thesis objective 5.** The remainder of the chapter is organised as follows; Section 5.2 describes the study catchments, their characteristics and details of the data used in reconstructing river flows. Section 5.3 presents the methods, including the hydrological model employed, calibration, validation and metrics used to assess model performance. Methods of drought identification are also described. Section 5.4 presents the results while sections 5.5 and 5.6 provide discussions and conclusions respectively.

5.2 Study catchments and data

Twelve catchments (see Figure 5.1) were chosen from the Irish Reference Network (IRN) for the purpose of flow reconstruction. These were chosen to account for a range of catchment characteristics (see Table 5.1) and the proximity of long term rainfall gauges from the IIP network. Among the twelve catchments selected area varies from 63 to 2460 km^2. The portion of flow (m^3/s^1) during low flow periods that derives from stored sources such as groundwater is defined by the Base Flow Index (BFI) The BFI for the study catchments ranges from 0.28 to 0.73; a low BFI (0.15 to 0.35) indicates a river which has minimal storage with flow being runoff dominated. In contrast a higher BFI means a catchment has a greater groundwater component (Gustard *et al.,* 1992). Thus, selected catchments provide a diverse sample to test the methods employed for reconstruction. Flow data for each catchment was obtained from the Office of Public Works (OPW). The daily mean flow data for each was downloaded from the OPW hydro webpage (http://waterlevel.ie/hydro-data/search.html) and converted to mean monthly flows.The IIP station nearest to each study catchment was identified. Figure 5.1 shows the location of the IIP stations in relation to each catchment. Note that Shannon Airport (7) is matched to two catchments (27002, 23002) and for some catchments the rainfall gauge is located outside of the catchment boundary.

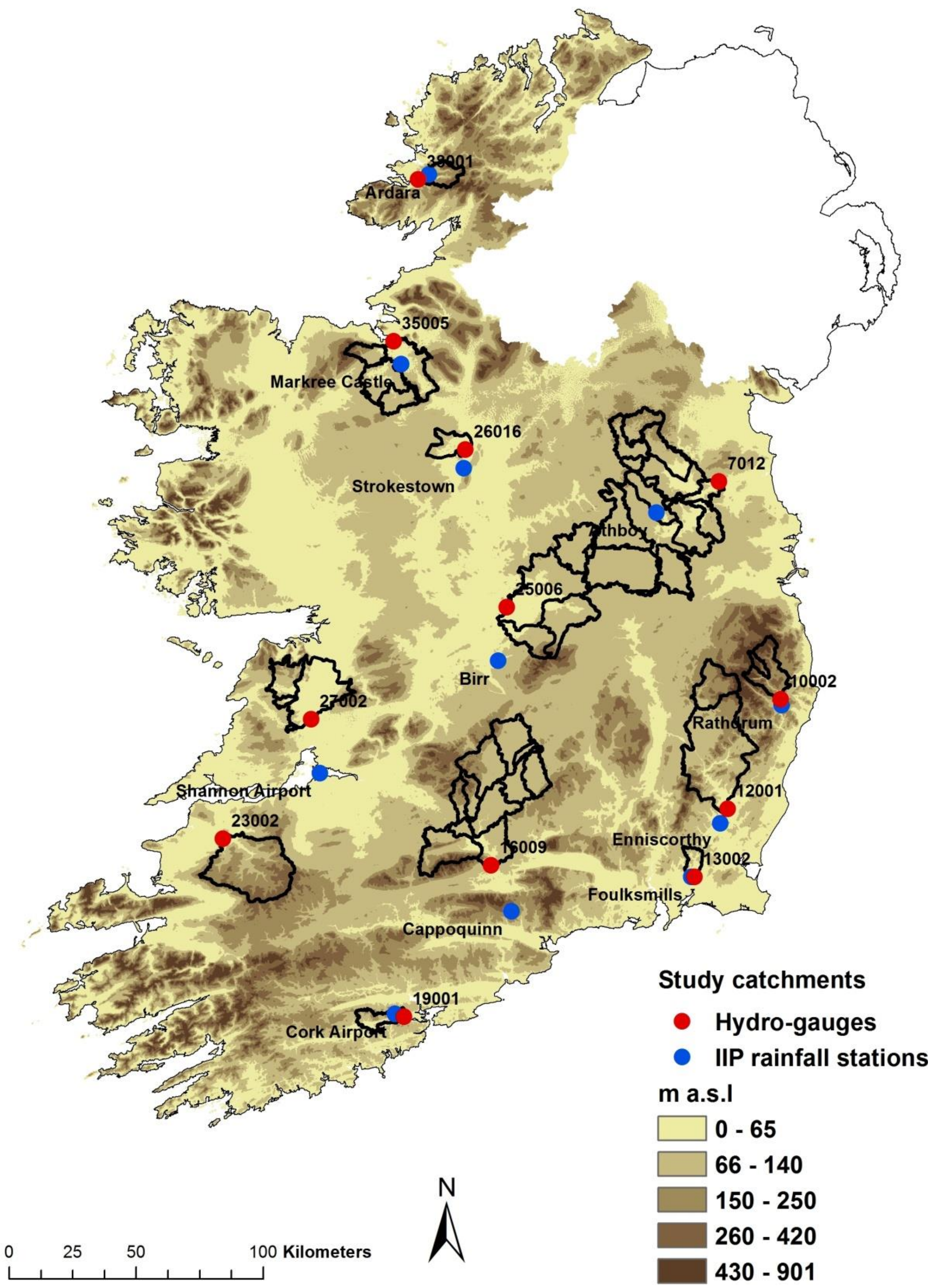


Figure 5.1 The location of the 12 study catchments (black outline) with the gauge location (red circle) and gauge number. The blue circles represent each of the Island of Ireland precipitation stations used in reconstructing river flow at each study catchment.

	Catchment Gauge ID											
Key Catchment Descriptors	**7012**	**10002**	**12001**	**13002**	**16009**	**19001**	**23002**	**25006**	**26018**	**27002**	**35005**	**38001**
Catchment Area (km²)	2460	231	1031	63	1583	106	647	1163	119	564	640	111
Standard-period (1961-1990) average annual potential evapotranspiration (mm)	890	1530	1167	1044	1079	1176	1345	932	1044	1336	1198	1753
Standard-period (1961-1990) average annual rainfall (mm)	504	511	522	537	518	527	514	495	458	533	463	498
BFI soils	0.68	0.54	0.72	0.73	0.63	0.68	0.31	0.71	0.72	0.70	0.61	0.28
Total length of river network above gauge (km)	2146	239	1101	65	1585	108	719	846	99	303	836	264
Main stream length (km)	94	35	89	16	85	24	51	67	25	40	41	26
Slope of main stream (m/km)	0.70	6.90	2.10	4.95	1.00	3.74	4.31	0.75	0.55	1.22	1.15	5.95
Proportion of catchment area mapped as benefitting from arterial drainage schemes	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00
Proportion (as a %) of river network length included in arterial drainage schemes	61	00	00	00	00	00	00	51	00	00	00	00

Table 5.1 Details of key catchment characteristics for each of the 12 selected study catchments (Source: Office of Public Works, Ireland)

In Ireland Met Éireann employ the widely-used Penman-Monteith method (Allen *et al.*, 1998) for calculating PET. Unfortunately, records for PET only span from the 1950's to date and therefore are not long enough to use in river flow reconstruction to 1850. There are other methods for calculating PET, but most have significant input data requirements such as temperature, wind speed and radiation. More parsimonious PET calculation methods that only require mean daily/monthly temperature and the latitude of the site include the Thornthwaite (1948) and Blaney-Criddle (1950) methods. However, in light of the lack of long-term quality assured temperature records for Ireland this study employs constant monthly PET over the period of reconstruction (1850-2015) by using the long-term monthly averages of the Met Éireann records 1955-2015.

Long-term average PET (LTA_PET) is calculated from seven synoptic station records from inland and coastal locations (Figure 5.2). Firstly, the monthly mean of each station was calculated and then averaged across all stations to obtain the long-term monthly averages employed for reconstruction. Figure 5.2 shows the long-term monthly mean at each of the seven PET stations together with composite mean across all stations. The monthly mean PET derived for this study closely corresponds to those values presented in Keane, (1986, p.69). Jones (1998) and Jones *et al.*, (2006) also used seasonally constant evapotranspiration calculated from long-term averages to reconstruct river flow, noting a more accurate monthly river flow model. The same studies note that constant evapotranspiration is useful for past reconstructions when only rainfall data are available.

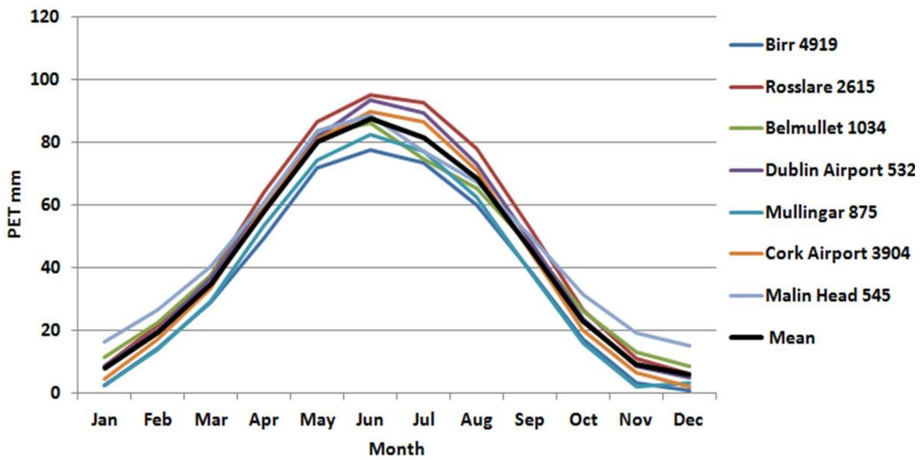


Figure 5.2 Long-term monthly mean PET at the seven Met Éireann stations from the mid 1950's to date. The black line represents the mean of all seven stations. (Data source: Met Éireann).

To evaluate the sensitivity of simulated flows to different PET data the hydrological model (detailed below) was run at two test catchments (35005 located in the west and 7012 in the east) to assess differences in output when only PET is varied. These two catchments were chosen to represent contrasting PET regimes between the east and west, proximity to available PET data sites and varying annual precipitation with 1200 mm per annum at 35005 and 900 mm at 7012. Available mean monthly temperature records at Markree Castle and Phoenix Park for the period 1873-2015 were used to calculate PET using the Thornthwaite equation (henceforth called TW_PET). Thornthwaite's method only requires mean monthly air temperature and latitude coordinates of each site and is estimated based on number of sunshine hours (Thornthwaite, 1948). Monthly Penman Monteith PET (henceforth PM_PET) data from two nearby synoptic stations (Belmullet and Dublin Airport) was also employed (1955-2010). Belmullet located in the west and Dublin Airport in the east. The three PET datasets (LTA_PET, TW_PET and PM_PET) a are used to run the hydrological model at two study catchments to examine the sensitivity of simulated flows to different PET input

5.3 Methods

5.3.1 The Hydrological Model

The hydrological model Hysim was chosen to reconstruct river flows for each catchment. HYSIM is a lumped conceptual rainfall runoff model (CRR) (Manley, 2006) that requires monthly/daily precipitation and PET data to simulate river flow. The model has been used previously to model Irish catchments (e.g. Charlton and Moore, 2003; Murphy *et al.*, 2006; Murphy *et al.*, 2013) and has been widely used across the UK and other countries (e.g. Pilling and Jones, 2002; Lennard *et al.*, 2015; Remesan and Holman, 2015; Soundharajan *et al.*, 2016). HYSIM is also being employed by Irish Water for yield assessment in developing a national water plan (Murphy, C. pers. comm.).

HYSIM uses parameters for hydrology and hydraulics that realistically characterize the river basin and channels. The model has a set of linked storage functions which connect seven natural stores (snow storage, interception, upper and lower soil horizon, transitional groundwater, groundwater storage and minor channel storage) representing the hydrological processes of the catchment (Murphy *et al.*, 2006). Figure 5.3 provides an overview of model structure and the linkages between stores. HYSIM has two sub–

routines; the first simulates the catchment hydrology and the second simulates the channel hydraulics.

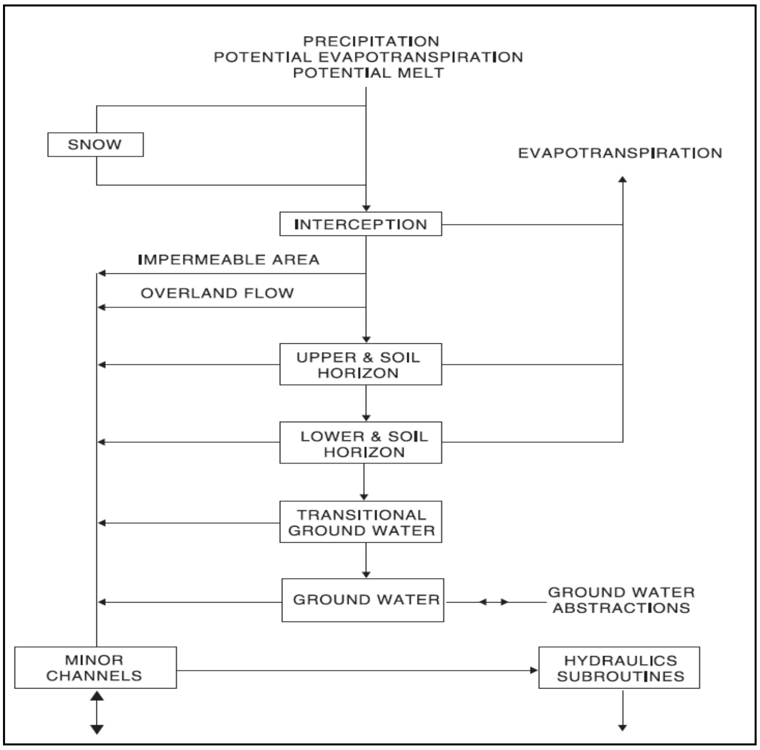


Figure 5.3 HYSIM model structure. Source (Murphy *et al.*, 2006)

HYSIM is more physically based and has more parameters with more physically realistic interpretation than traditional lumped CRR models (Manley, 2006). HYSIM has two main groups of parameters; physical parameters and process parameters. The physical parameters are measurable properties of the watershed; the process parameters represent the characteristics that are not directly measurable. Physically based parameters were set using prior knowledge of soil type, catchment size and past flow records (Manley, 2006). Process parameters need to be calibrated by comparing observed and simulated flows. These include the interflow parameters and two permeability parameters which control movement of water in the soil layers.

To derive estimates of the process parameters model calibration can be performed manually or by automatic methods. The manual method uses a trial and error process of parameter adjustments. However, a major limitation of the manual method is the subjectivity involved in the process. The lack of generally accepted objective measures of model evaluation makes it difficult for the user to decide when to end the calibration process (Sooroshian and Gupta, 1995). Automatic calibration methods allow for a much quicker model calibration and include some measure of objectivity and confidence to the model. HYSIM has a number of automatic calibration options; single parameter optimisation, multi-parameter optimisation and no optimisation. If the no optimisation is used then the manual based approach is adopted and the model is only run once.

The single parameter technique selects a single parameter which is varied to construct a flow balance. The iterative Newton-Raphson method of successive approximation is employed. The parameter search method adjusts one chosen parameter until the modelled mean flow is correct with some degree of accuracy. The multi-parameter optimisation changes several parameters using an optimisation algorithm, to achieve the optimum value in the parameter space or response surface. The *Multi-Parameter Optimisation* method in HYSIM is dealt with by the Rosenbrock method (Manley, 2006). Parameters involved in this calibration process are the two interflow parameters and the two permeability parameters. Additionally the Pore Size Distribution Index (PSDI) and rooting depth parameters can also be fine tuned during this process.

HYSIM has four in-built objective functions that provide a measure of fit between simulated and observed flows and can be used for multi-parameter calibration. The Proportional Error of estimate (PEE) is a function that leads to a minimisation of proportional errors. The PEE is useful when only low flows are of interest (Manley, 2006). The Reduced Error of Estimate (REE) gives equal weight to equal errors and is useful for flood modelling or for catchments where flow during summer is zero or near zero (Manley, 2006). The Extreme Error of estimate (EEE) gives greater weight to both high and low extremes and is a general all purpose objective function (Manley, 2006). Finally, the Base Flow function is based on the sum of least squares of errors of base flow and can be used to avoid unnaturally low values from data errors. Here, the EEE objective function is employed as it is a general purpose objective function suitable for high and low flows.

The application of hydrological models is associated with many uncertainties, mainly due to a lack of knowledge of the specific hydrological system. The hydrological model simplifies catchment processes in order to simulate flow resulting in model structural uncertainties (Montanari & Brath, 2004; Murphy *et al.,* 2006). Other sources of uncertainty derive from parameter estimation and parameter identifiably. Equifinality exists where many model parameter combinations can generate a satisfactory simulation (Wilby, 2005). The difficulties of identifying the most appropriate parameter sets can cause substantial uncertainty in modelling the hydrological system (Wagener *et al.,* 2003; Wilby, 2005). This study acknowledges these uncertainties but as this is an initial first pass at reconstructing Irish river flows a single optimised model structure is employed.

The following steps were employed for model calibration and validation:

Step 1: For each catchment a suitable period from the observed flow records (good quality data and free from non-climatic influence such as drainage) was identified for calibration and validation. Calibration was conducted using over 75% of the selected record and the balance was used for model validation (Murphy *et al.,* 2006; Remesan and Holman, 2015).

Step 2: For each catchment a parameter file was created by inputting the initial hydrology parameters such as catchment area, time to peak, interception storage and rooting depth which were estimated from catchment characteristics and flow records, all other parameters were left at default and/or fitted during calibration.

Step 3: The first step of calibration was to establish a water balance by running the model in single parameter optimisation mode for precipitation and saving the parameters.

Step 4: Process parameters were then fitted in automatic calibration mode using the EEE objective function. Parameters fitted in this way include; the horizon boundary permeability, base horizon permeability, upper and lower soil interflow parameters. The parameters were saved and performance assessed visually.

Step 5: Finally validation was conducted by running the model for an independent period of record with simulated flows compared with the observed flows.

Several goodness of fit criteria were also calculated to assess model performance. The Nash Sutcliffe Efficiency (NSE) is commonly used to assess model performance but is biased towards peak flows (Muleta, 2011). An efficiency of 1 (NSE = 1) corresponds to a perfect match of simulated and observed flow. As this study was interested in identifying low flows additional statistical goodness of fit measures were employed, including; the Mean Absolute Error (MAE), Percent Bias (PBIAS) and coefficient of determination (R^2). Full details on each of these statistical performance criteria are given in Muleta (2011). Model performance was assessed by separating the calibration and validation periods at each catchment into summer half year (Apr, May, Jun, Jul ,Aug and Sep) and winter half year (Oct, Nov, Dec, Jan, Feb and Mar).

5.3.2 Drought identification

To identify periods of drought in the reconstructed series (1850-2015) two drought indices were used which permit the identification of discrete drought events with defined duration. A widely used method for drought identification in river flows is the threshold level approach (Hisdal *et al*., 2001; Fleig *et al*., 2006) where the start and end of a drought is defined by a period when flow is below a certain threshold. The Q95 flow index relates to the flow exceeded 95 percent of the time and is an important low flow indicator. Q95 is widely used for monitoring water quality and supply and is thus adopted as a flow threshold. Q95 thresholds were calculated for each month of the year for each reconstructed flow series (Watts *et al.,* 2015). The full reconstructed period (1850-2015) is used to derive monthly Q95 values. The identification of thresholds for each month allows multi-season droughts to be identified. The start of a drought is defined when simulated flows drop below the long term Q95 value for that month and ends when the Q95 returns to a positive value (i.e. above the long term Q95 value for that month).

The Drought Severity Index (DSI) was also derived. DSI calculates runoff deficiencies as an anomaly relative to the baseline 1961-1990. The current climate baseline period recommended by the WMO is 1961-1990. This baseline period has been used in numerous climate studies (e.g.Wilby and Harris, 2006; McElwain and Sweeney, 2007; Prudhomme and Davies 2009; Sexton and Harris, 2015) to inform policy makers of both past and future climatic change as well as changes in extremes relative to this baseline period. The period 1961-1990 was relatively dry across the Irish and British Isles (Wilby *et al.,* 2015) with particularly dry summers identified over the period prior to the late 1970's (Matthews *et al.,* 2015). These findings are also supported by Baines and Folland (2007) who found that northwest Europe was relatively dry during the period of cool sea surface temperatures in the North Atlantic around the 1970s. Therefore, any identified drought periods relative to this period would be noteworthy.

To calculate the DSI, monthly values are first expressed as an anomaly relative to this baseline period. Using the DSI drought commences when a period of negative deficiency starts with negative deficits accumulated until drought ends when the DSI reaches positive values (Bryant *et al.*, 1998; Fowler and Kilsby, 2002; Watts *et al.*, 2015). To assess the accumulated flow deficits the 12 month running mean DSI flow deficit as a percentage of the 1961-1990 baseline was also calculated.

Recently several studies have assessed whether the Standardised Precipitation Index (SPI) can be used as a forecast tool for hydrological drought and flood events in river flow (Du *et al.*, 2013; Wang *et al.*, 2015; Barker *et al.*, 2015). Correlations between SPI and observed Q95 flow are investigated to provide an indication of the time it takes for precipitation deficits to circulate through the catchment into river flow deficits and to establish the potential for SPI use as a drought forecasting tool in different catchments. This study derives SPI values for accumulation periods of 1-6 months for stations within the IIP network and uses Spearman's correlation (r_s) to cross correlate monthly SPI and observed Q95 flow. This test is applied to four sample catchments; 38001 and 23002 with low BFI values (runoff dominated catchments) and 12001 and 27002 with high BFI (groundwater dominated catchments). Lagged relationships between SPI (accumulation periods 1-6 month) and observed Q95 flows at each catchment are assessed for lags of up to 5 months.

Finally the influence of the North Atlantic Oscillation Index (NAO) on Irish river flow is investigated. Reconstructed seasonal flows are correlated with the seasonal NAO using Spearman's correlation. Summer flow is also correlated with the previous winter's NAO given that previous research has identified lagged relationships in shorter records (Murphy *et al*., 2013). The station based NAO data from 1866-2015 is employed and downloaded from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based

5.4 Results

5.4.1 Model sensitivity to PET.

The sensitivity of modelled output to different PET series was assessed for two contrasting catchments. Ballysadare 35005 located in the west was calibrated over the period (1990-2000) with model validation undertaken for (2001-2010). Boyne 7012 in the east of the island was calibrated for 1960-1970 and validated for 1990-2000. These choices of calibration validation periods were constrained by the availability of good quality river flow record and PET data. Goodness of fit measures (NSE, MAE, PBIAS and R^2) were derived for flows over the entire calibration and validation periods and winter and summer half years. Table 5.2 presents results of the assessment for each of the three PET estimation methods for the entire calibration and validation periods in both catchments.

	Goodness of fit test	**7012-Boyne (Cal 1960-1970) (Val 1990-2000)**			**35005-Ballysadare (Cal 1990-2000) (Val 2001-2010)**		
		LTA_PET	**TW_PET**	**PM_PET**	**LTA_PET**	**TW_PET**	**PM_PET**
Cal	NSE	0.89	0.86	0.90	0.81	0.83	0.80
	R^2	0.88	0.86	0.89	0.86	0.85	0.86
	MAE (m^3/s^1)	6.63	7.48	6.33	3.97	3.94	4.19
	PBIAS (m^3/s^1)	-0.6	-0.7	-3.2	5.5	-9.3	4.1
Val	NSE	0.78	0.77	0.80	0.76	0.76	0.81
	R^2	0.80	0.79	0.72	0.82	0.80	0.80
	MAE (m^3/s^1)	9.79	10.72	12.44	4.19	4.06	4.29
	PBIAS(m^3/s^1)	4.3	-18.7	-18.8	3.3	-11.9	-2.1

Table 5.2 Calibration (Cal) and validation (Val) performance using three different PET estimation methods: long-term averge PET (LTA), Thorntwaite PET (TW) and Penman Monteith PET (PM). Table shows the goodness of fit results for NSE, R^2, MAE and PBIAS at two study catchments 7012 and 35005 for the full calibration and validation periods.

The results goodness of fit are compared for each catchment separately with no comparison between catchments. Calibration results at Boyne 7012 show all three methods performed well in capturing the observed flows. There are slight differences in terms of the best performing PET method depending on the goodness of fit measure. Best PBIAS scores are returned using the long term average method at Boyne 7012, also being the case for validation. During validation at Boyne 7012, large errors (~18%) are evident for PBIAS using the Thornthwaite and Penman methods. Results for the full calibration period at 35005 1990-2000 show little difference between each of the three PET methods for this catchment (Table 5.2). Results at Ballysadare 35005 over the full validation period 2001-2010 show a similar model performance, with only minor differences across each of the PET methods. The importance of PET estimation is greatest in the eastern catchment where evaporative losses are greatest and the use of long term average PET provides better simulations for PBIAS relative to other methods. Figure 5.4 plots simulated and observed flows for winter (Oct, Nov, Dec, Jan, Feb and Mar) and summer (Apr, May, Jun, Jul ,Aug and Sep) half years during validation at both catchments. Table 5.3 shows goodness of fit statistics for each catchment for winter and summer half years during calibration and validation. At Ballysadare 35005 the LTA_PET method performs best in both winter and summer. Similarly at Boyne 7012 both TW_PET and PM_PET methods show very high PBIAS - greater than -25 per cent for summer during validation. Summer validation results clearly show that LTA_PET model returns the best model fit, with the highest NSE and the lowest PBIAS (-7.1 per cent). Thus the long term average PET was adopted for use in subsequent modelling.

	PET model	**NSE**		**MAE (m^3/s^1)**		**PBIAS (m^3/s^1)**	
		35005	**7012**	**35005**	**7012**	**35005**	**7012**
Cal (Winter)	*LTA*	0.62	0.82	5.51	8.44	11.7	-0.7
	TW	0.72	0.83	4.51	8.61	-4	-4.6
	PM	0.62	0.82	5.51	8.70	10.6	-5.3
Val (Winter)	*LTA*	0.64	0.63	5.33	13.48	9.4	8.1
	TW	0.65	0.62	4.90	14.55	-7.5	-16.3
	PM	0.64	0.68	5.22	12.99	8.1	-16.2
Cal (Summer)	*LTA*	0.623	0.89	2.43	6.20	-12.9	-6.4
	TW	0.35	0.86	3.34	7.13	-25.41	-2
	PM	0.56	0.87	2.87	7.03	-15.4	-1.3
Val (Summer)	*LTA*	0.51	0.62	3.06	6.09	-11.5	-7.1
	TW	0.45	0.60	3.23	6.97	-22.6	-25.8
	PM	0.42	0.57	3.36	6.18	-12.4	-26.5

Table 5.3 Calibration (Cal) and validation (Val) performance for winter and summer half years using long-term averge PET (LTA), Thorntwaites PET(TW) and Penman Monteith PET (PM). Table shows NSE, R^2, MAE and PBIAS results for both test catchments.

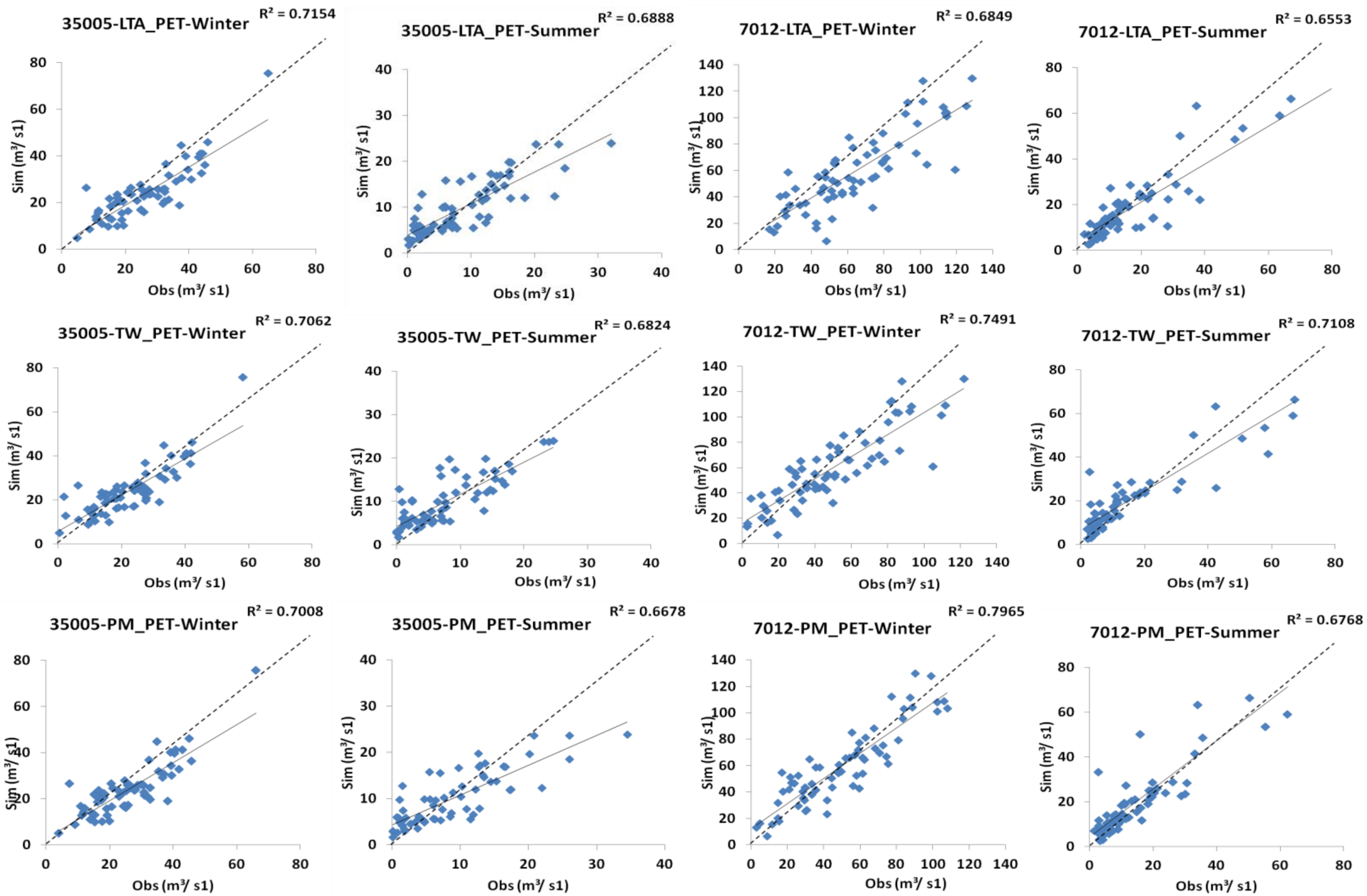


Figure 5.4 Validation results for the PET sensitivity test using long-term averge PET (LTA), Thorntwaites PET(TW) and Penman Monteith PET (PM) at two study catchments 35005 (2001-2010) and 7012 (1990-2000). The plots show observed and simulated flows over the winter half year (Oct, Nov, Dec, Jan, Feb and Mar) and summer half year (Apr, May, Jun, Jul ,Aug and Sep). The solid black line indicates the best fit and dotted line indicates a perfect fit.

5.4.2 Model calibration and validation

Model calibration and validation results over the full period of assessment for the twelve study catchments are presented in Table 5.4. The results show overall good model performance during calibration with NSE values ranging from 0.76 at 12001 to 0.91 at 38001. Validation NSE results range from 0.67 at 12001 to 0.92 at 26018. R^2 correlation results are similar to the NSE results. PBIAS results indicate that the models have some underestimating bias ranging from -0.6% to -11.2%. The largest PBIAS values for calibration -11.2% are found for catchment 23002. It is noted that this is one of the catchments where the precipitation gauge is located outside the catchment, which could account for poorer performance. For the majority of catchments validation model performances are not greatly reduced from the calibration results, indicating that the models are not over trained on the calibration data. One exception is catchment 16009 where validation results are considerably poorer than those obtained for calibration. Again, this is a case where the rainfall station may not be adequately representative of the catchment. Figure 5.5 compares scatter plots of simulated and observed flows for the summer half year at each catchment during validation. Best performance is obtained for catchment 7012 (R^2 = 0.87). Catchment 27002 (R^2 = 0.59), 16009 (R^2 = 0.59) and 12001 (R^2 = 0.56) show the poorest results. As flagged previously weaker results at 16009 may be due to the rainfall not adequately representing the catchment. Validation results for the summer half year at the remaining catchments show R^2 values ranging from 0.62 to 0.75.

The winter half year validation scatter plots are presented in Appendix 3 and reveal R^2 values ranging from of 0.66 to 0.93. The weakest winter half year validation scores were at 12001 which are similar to the summer half year results. This is a large catchment and with the upper reaches of the catchment draining the Wicklow Mountains before flowing south. The rain gauge used to model the catchment (Enniscorthy) is located at much lower elevation and thus likely underestimates precipitation for the catchment. Despite weaker performance at a couple of catchments, overall models show an acceptable level of performance during calibration and validation. Therefore validated models were used to reconstruct river flow at all twelve study catchments for the period 1850-2015. Figures 5.6 and 5.7 show the flows over the entire reconstructed period for winter and summer half years. Also plotted are the observed flows at each of the twelve study catchments.

Catchment	Catchment Area (km^2)	Model	Period	NSE	R^2	MAE m^3/s^1	PBIAS m^3/s^1
7012-Boyne	2460	Cal	1942-1960	0.88	0.89	6.76	3.1
		Val	1961-1970	0.90	0.93	5.43	0.6
10002-Avonmore	231	Cal	1953-1964	0.77	0.93	2.13	-1.3
		Val	1965-1970	0.88	0.86	2.13	-6
12001-Scarrawalsh	1031	Cal	1990-2010	0.76	0.74	5.61	-2.6
		Val	1970-1980	0.67	0.77	5.12	5.6
13002-Corock	63	Cal	1977-1982	0.88	0.92	0.21	-1.1
		Val	1983-1985	0.83	0.83	0.20	-3.4
16009-Suir	1583	Cal	1953-1980	0.84	0.84	6.16	-0.6
		Val	1991-2000	0.68	0.77	9.12	-12.1
19001-Owenboy	106	Cal	1974-1990	0.84	0.84	0.64	-1.9
		Val	1991-2010	0.83	0.88	0.57	-1.7
23002-Feale	647	Cal	1974-1990	0.84	0.87	4.86	-11.2
		Val	1991-2010	0.87	0.88	4.61	-2.41
25006-Brosna	1163	Cal	1952-1960	0.89	0.85	3.58	-1.7
		Val	1961-1970	0.77	0.84	4.09	-5.4
26018-Owenure	119	Cal	1992-2000	0.89	0.87	0.59	1.3
		Val	1976-1980	0.92	0.93	0.39	0.8
27002-Fergus	564	Cal	1974-1985	0.88	0.88	2.18	6.4
		Val	1986-1990	0.79	0.81	2.44	-0.8
35005-Ballysadare	640	Cal	1947-1960	0.84	0.84	2.84	-0.7
		Val	2002-2008	0.76	0.82	3.21	-4.6
38001-Ownea	111	Cal	1994-2000	0.91	0.95	0.88	1.7
		Val	2001-2003	0.889	0.91	0.78	-0.7

Table 5.4 Model calibration (Cal) and validation (Val) performance at each catchment.

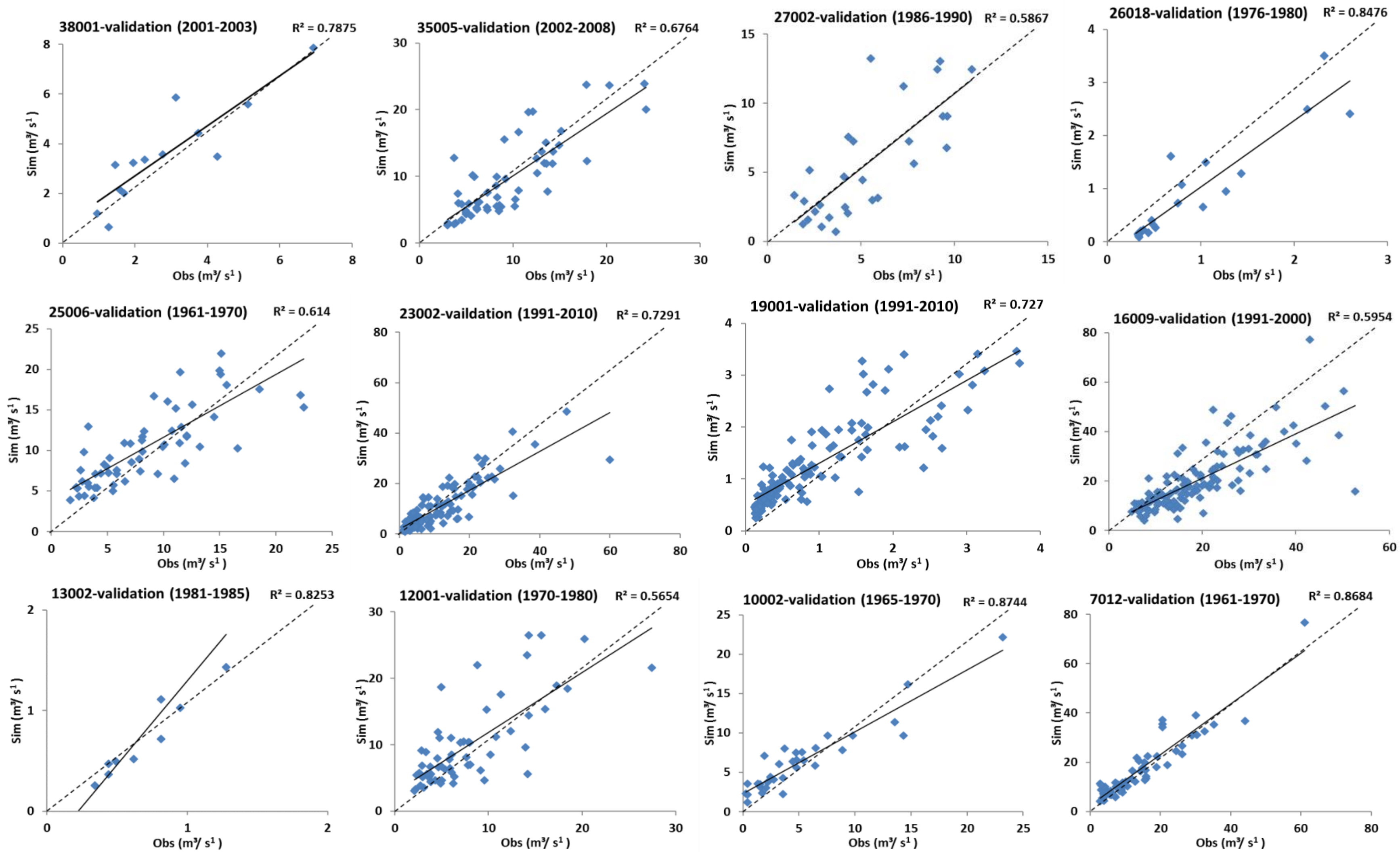


Figure 5.5 Scatter plots of simulated and observed summer half year flows for the validation period at each study catchment. The solid black line indicates the best fit and dotted line indicates a perfect fit.

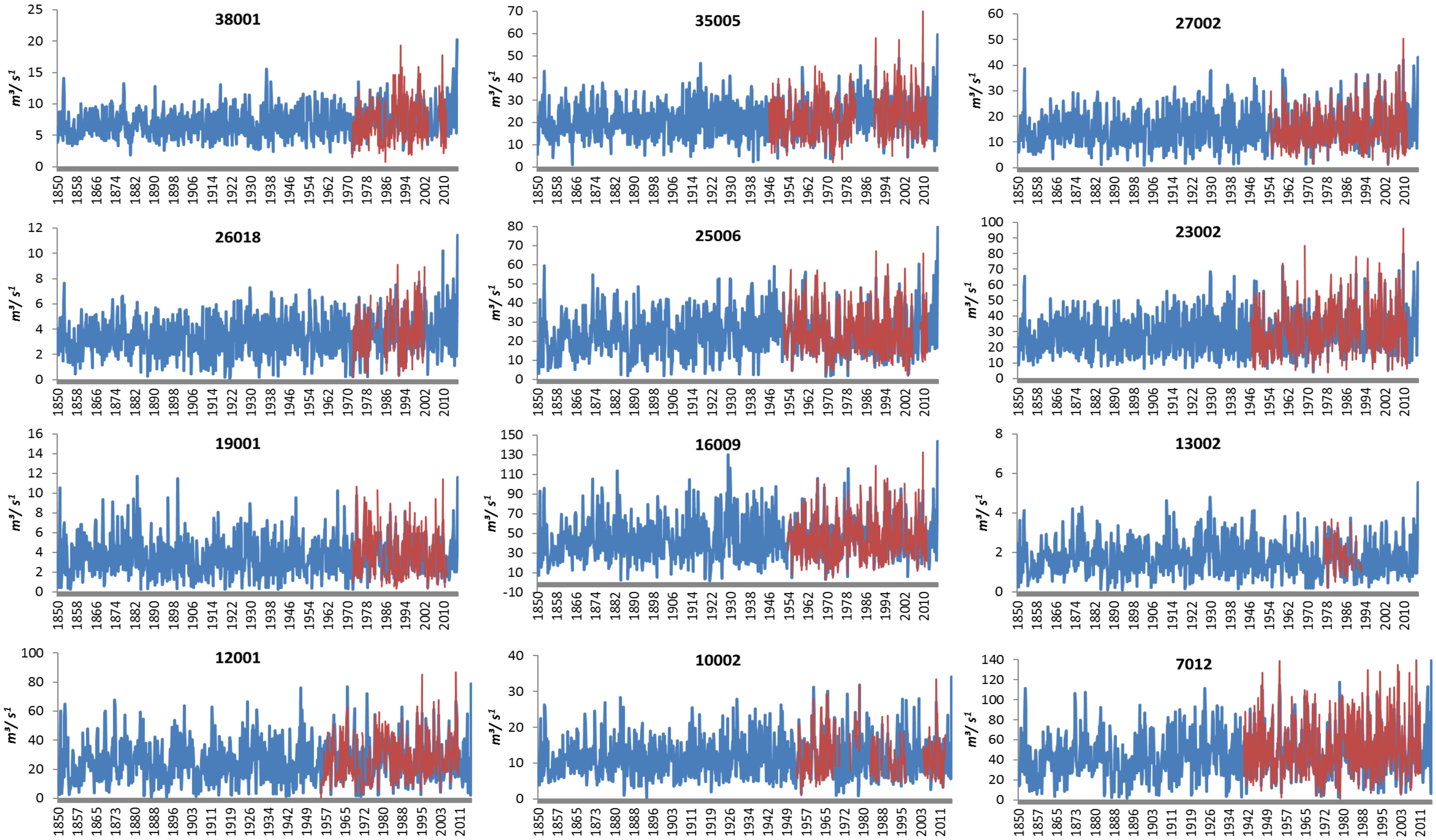


Figure 5.6 Reconstructed (1850-2015) (blue line) and observed (red line) flows for the winter half year for each of the twelve catchments

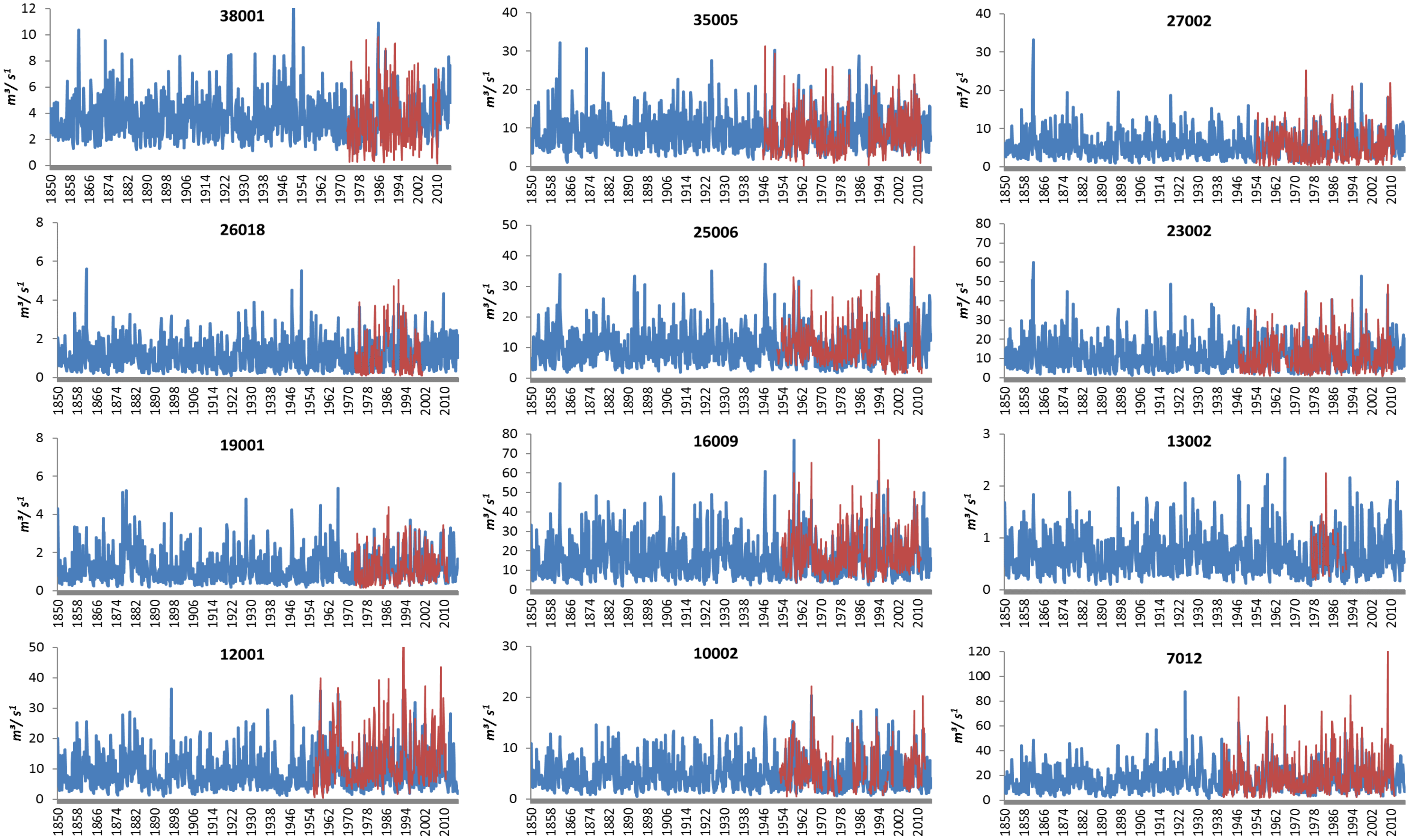


Figure 5.7 Same as Figure 5.6 but for summer half year flows.

5.4.3 Drought identification

5.4.3.1 Drought Severity Index

The Drought Severity Index (DSI) was applied to reconstructed flows to calculate monthly runoff deficiencies relative to the baseline 1961-1990. Using this indicator drought is defined as starting with a period of negative deficiency and ends when the DSI values become positive (Watts *et al.*, 2015). Table 5.5 shows the top three drought events based on drought duration as derived from DSI for each catchment. Appendix 4 presents the top ten ranked DSI results based on duration and shows the drought start and end dates, duration and mean and accumulated deficits of each event at each catchment. The results show that the study catchments have experienced DSI deficits relative to the baseline 1961-1990 lasting up to 22 months. The most notable drought years occurred in 1854-1860 when droughts affected most catchments at various times, lasting between 9 and 22 months during this period. Another noteworthy drought that affected all catchments occurred during 1887-1888 with drought lasting between 9 to 21 months across catchments.

During 1890 to 1891 drought lasted for 22 months at 7012 (BFI .68) in the east and also affected 10002 (BFI .54) (also in the east) but only lasted 9 months (Table 5.5 and Appendix 4). The drought in 1893-1894 only appears to have affected catchments Boyne 7012 (BFI. 68), Avonmore 10002 (BFI .54), Scarrawalsh 12001 (BFI .72), Corock 13002 (BFI .73), Owenure 26018 (BFI .72), Fergus 27002 (BFI .70) in the southwest, west, southeast and east lasting between 9 and 10 months. The results of chapter 4 show that meteorological drought lasted up to 76 months in the east and up to 53 months in the southeast, considerably longer than the hydrological drought identified here. The differences in drought duration are more than likely due to the majority of these catchments being dominated by groundwater and hence more storage is available to sustain flow. Another significant drought occurred between 1906 and 1907. This drought mostly affected Scarrawalsh12001 (BFI .72) and Corock 13002 (BFI .73) with drought lasting up to 22 months in the southeast.

Catchment and location	Rank	Drought Start	Drought end	Mean DSI m³/ s1 Deficit	Accumulated DSI m³/ s¹ Deficit	Drought duration months
38001	1	1856-02	1856-12	-2.13	-21.28	10
(BFI .28)	2	1888-01	1888-11	-1.57	-15.68	10
	3	1933-03	1934-01	-3.11	-31.08	10
35005	1	1855-01	1855-12	-6.58	-72.39	11
(BFI .61)	2	1864-02	1865-01	-9.58	-105.37	11
	3	1856-03	1857-01	-8.13	-81.32	10
27002	1	1855-01	1856-01	-4.43	-53.14	12
(BFI .70)	2	1888-01	1888-11	-4.53	-45.26	10
	3	1993-02	1993-12	-3.33	-33.33	10
26018	1	1855-02	1856-01	-1.15	-12.66	11
(BFI .72)	2	1921-02	1922-01	-1.49	-16.42	11
	3	1858-02	1858-12	-0.90	-9.02	10
25006	1	1887-03	1888-12	-7.60	-159.67	21
(BFI .72)	2	1975-03	1976-10	-7.93	-150.68	19
	3	1850-01	1850-12	-8.30	-91.32	11
23002	1	1933-02	1934-01	-9.83	-108.16	11
(BFI .31)	2	1919-02	1919-12	-10.15	-101.47	10
	3	1963-12	1964-10	-5.02	-50.20	10
19001	1	1906-03	1907-11	-1.55	-31.04	20
(BFI .68)	2	1854-02	1855-03	-1.67	-21.73	13
	3	1917-02	1918-01	-1.06	-11.69	11
16009	1	1854-03	1855-12	-15.50	-325.40	21
(BFI .63)	2	1850-01	1850-12	-17.33	-190.65	11
	3	1991-12	1992-11	-9.27	-101.99	11
13002	1	1854-03	1855-12	-0.55	-11.63	21
(BFI .73)	2	1906-03	1907-11	-0.53	-10.55	20
	3	1975-03	1976-11	-0.70	-13.93	20
12001	1	1854-02	1855-12	-11.16	-245.49	22
(BFI .72)	2	1906-03	1907-10	-13.58	-258.11	19
	3	1887-02	1888-01	-11.92	-131.07	11
10002	1	1991-12	1992-11	-3.76	-41.40	11
(BFI.54)	2	1948-02	1948-12	-2.64	-26.36	10
	3	1854-02	1854-11	-4.68	-42.09	9
7012	1	1890-02	1891-12	-20.30	-446.50	22
(BFI .68)	2	1855-01	1856-01	-16.27	-195.28	12
	3	1906-03	1907-03	-17.92	-215.04	12

Table 5.5 Top three DSI drought events relative to baseline 1961-90 ranked by duration (months) at all catchments (1850-2015). The drought start period is defined when the DSI value becomes negative and ends when the DSI value returns positive. Also shown are drought start and end dates together with the duration in months, mean DSI deficit (m^3/ s^1) and accumulated DSI deficit (m^3/ s^1)

Chapter 4 results show that meteorological drought persisted for up to 39 months in the southeast and again the differences are probably due to groundwater storage. Drought occurred during 1933-1934 mainly across all except Suir 16009 (BFI .63), Corock 13002 (BFI .73), Scarrawalsh12001 (BFI .72), Avonmore 10002 (BFI .54) and Boyne 7012 (BFI .68) and lasted up to 11 months at Feale 23002 (BFI .31). Feale 23002 catchment has one of the lowest BFI's (.31) but the hydrological drought is still much shorter than the 32 months of meteorological drought identified across the southwest in chapter 4. Other periods during the 1940s, 1970s and 2003 also feature strongly as experiencing droughts at catchments at different locations for varying time periods (Table 5.5 and Appendix 4).

Figure 5.8 plots 12 month running mean DSI deficits as a percentage of the baseline 1961-1990 for the twelve study catchments. Appendix 5 presents the ten longest 12 month running mean DSI deficits at the twelve study catchments. Owenboy 19001 (BFI .68) shows DSI flow deficits 75% below the 1961-90 baseline during January and February 1885. The same catchment has DSI deficits of greater than 60% below the baseline in 1854. DSI flow deficits of -60% are shown at the Boyne 7012 (BFI .68) during 1891, 1934 and 1888. At Scarrawalsh 12001 (BFI .72) DSI deficits of -60% are also evident in 1907, 1894, and 1855. In 1976 DSI flow deficits at Corock 13002 (BFI .73) peaked at 64% less than the mean baseline 1960-91. According to the DSI 12 month running mean the longest continuous deficits occurred at 35005 (BFI .61) during 1884-1894 lasting 120 months (Appendix 5). Similar to the previous results the most notable droughts in terms of duration occurred during the years 1854-1860 (Figure 5.8). The majority of catchments experience continuous 12 month mean deficits ranging between 33 months at Brosna 25006 (BFI .71) and 80 months at Suir 16009 (BFI .63) during 1854-1860.

The results presented in Figure 5.8 also indicate that a long drought persisted during 1887-1897. The drought duration ranged from 37 months at Brosna 25006 (BFI .71) to 118 months at Boyne 7012 (BFI .68). A drought rich period occurred at all catchments during 1904-1912 except Feale 23002 (BFI .31). The length of droughts during this period ranged from 27 months at Ownea 38001 (BFI .28) and 87 months at Scarrawalsh12001 (BFI .72). Other noteworthy droughts were identified during the 1920's, 1930's, 1950's, 1970's and the early 2000's (Appendix 5).

These results indicate that the larger catchments that are more groundwater dominant appear to have been more severely affected by drought since 1850. Results indicate that catchments Avonmore 10002 (BFI .54), Feale 23002 (BFI .31) and Ownea 38001 (BFI .28) were affected less severely from drought than the other catchments since 1850. Results at catchment 10002 (BFI .54) shows that the maximum DSI accumulated deficits only reached -56% and only one drought period exceeded 45 months in duration (1854-1860). Similar results at Feale 23002 (BFI .31) shows that the maximum DSI accumulated deficits only reached -50% and only one drought period lasted for longer than 50 months (1853-1860). Ownea 38001 (BFI.28) results shows a that the DSI accumulated deficits also only reached -53% and only two drought periods lasted longer than 45 months, 1853-1860 and 1929-1934. The results also indicate that there has been a decline in severity and length of droughts at all catchments in past 40 years.

5.4.3.2 Q95 threshold events

The Q95 threshold method was used to identify severe drought events from reconstructed flows. Table 5.6 shows the top three ranked Q95 drought events based on duration for each catchment. Also shown are the mean and accumulated deficits (m^3/s^1) and drought duration. Appendix 6 presents the ten longest duration Q95 drought events and shows the drought start and end dates, duration and mean and accumulated deficits of each event. The Q95 results show that drought occurred sporadically between 1854-1860 affecting most catchments at varying times during these years with periods of drought lasting 3 to 4 months. Brosna 25006 (BFI .71) experienced the most severe drought lasting 7 months from January to August 1850. The drought in 1887 more severely affected Brosna 25006 (BFI .71), Owenboy 19001 (BFI .68), Suir 16009 (BFI .63), Corock 13002 (BFI.73) and Scarrawalsh 12001 (BFI .71) with continuous Q95 flow deficits that ranged 6 to 9 months. Drought lasted 9 months at Brosna 25006 (BFI .71) in 1887 with the largest Q95 flow deficit of all catchments experienced in February 1888. Boyne 7012 (BFI .68) experienced the longest and most severe drought in 1891 with Q95 flow deficits lasting 8 months. Ownea 38001 (BFI .28) was least affected by drought in 1891 and only had one month of a Q95 flow deficit.

The 1893 drought most severely affected Corock 13002 (BFI .73), Scarrawalsh 12001 (BFI .72), Avonmore 10002 (BFI .54) and Boyne 7012 (BFI .68) with flows below long-term Q95 lasting 6 to 7 months. Boyne 7012 (BFI .68) experienced the highest Q95 flow deficts of all catchments in November 1893. However, the 1893 drought did not affect Owenboy 19001 (BFI .68) and Brosna 25006 (BFI .71) and Ballysadare 35005 (BFI .61) and Ownea 38801 (BFI .28) were only affected for three and two months respectively.

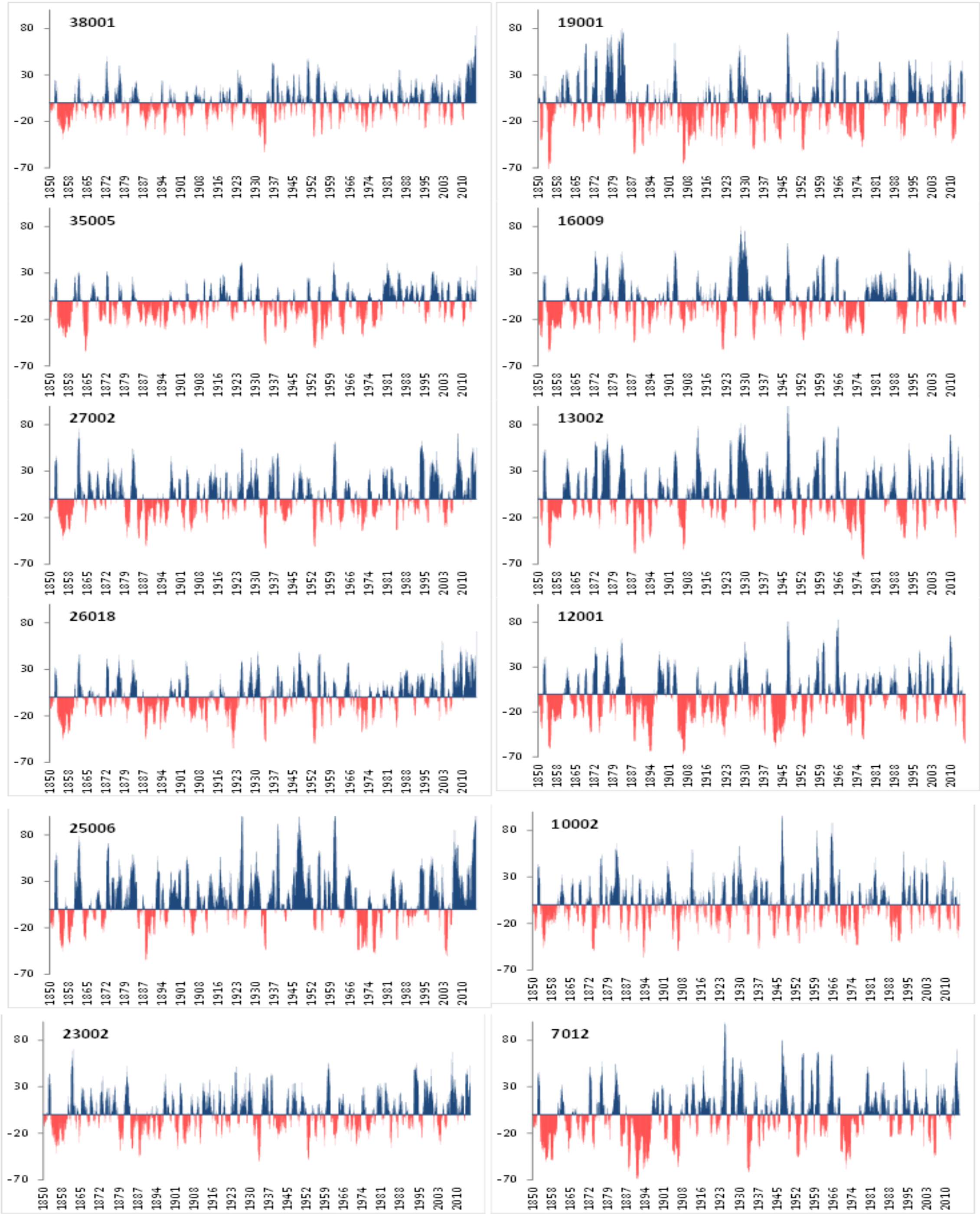


Figure 5.8 12 month running mean DSI anomalies 1850-2015 represented as an percentage relative to the 1961-1990 baseline average for each catchment.

Catchment and location	Rank	Drought Start	Drought end	Mean Q95 m³/ s¹ deficit	Accumulated Q95 flow m³/ s¹ Deficit	Drought duration months
38001	1	1953-01	1953-06	-0.20	-0.99	5
(BFI .28)	2	1929-03	1929-07	-0.42	-1.66	4
	3	1933-09	1934-01	-1.00	-3.99	4
35005	1	1864-02	1864-11	-1.08	-9.70	9
(BFI .61)	2	1953-01	1953-08	-1.69	-11.85	7
	3	1956-02	1956-07	-1.17	-5.87	5
27002	1	1891-02	1891-08	-0.57	-3.40	6
(BFI .70)	2	1893-04	1893-10	-0.24	-1.42	6
	3	1953-02	1953-08	-1.25	-7.51	6
26018	1	1921-05	1921-12	-0.26	-1.84	7
(BFI .72)	2	1893-04	1893-10	-0.02	-0.12	6
	3	1953-02	1953-08	-0.22	-1.31	6
25006	1	1887-07	1888-04	-1.30	-11.70	9
(BFI .72)	2	1850-01	1850-08	-1.71	-11.98	7
	3	1864-04	1864-10	-0.30	-1.80	6
23002	1	1893-03	1893-08	-0.61	-3.06	5
(BFI .31)	2	1902-07	1902-11	-0.82	-3.27	4
	3	1933-09	1934-01	-2.63	-10.53	4
19001	1	1944-02	1944-09	-0.16	-1.13	7
(BFI .68)	2	1887-05	1887-11	-0.06	-0.36	6
	3	1906-12	1907-05	-0.51	-2.55	5
16009	1	1887-05	1887-11	-1.25	-7.50	6
(BFI .63)	2	1921-07	1922-01	-4.12	-24.70	6
	3	1854-11	1855-03	-5.28	-21.10	4
13002	1	1975-12	1976-10	-0.20	-1.98	10
(BFI .73)	2	1887-06	1888-01	-0.07	-0.51	7
	3	1891-02	1891-08	-0.12	-0.73	6
12001	1	1893-06	1894-01	-1.43	-10.01	7
(BFI .72)	2	1944-03	1944-10	-1.05	-7.38	7
	3	2015-01	2015-08	-1.03	-7.19	7
10002	1	1893-04	1893-12	-0.77	-6.18	8
(BFI.54)	2	1874-04	1874-08	-0.41	-1.63	4
	3	1953-01	1953-05	-0.53	-2.13	4
7012	1	1891-01	1891-09	-6.48	-51.82	8
(BFI .68)	2	1893-06	1894-01	-3.31	-23.19	7
	3	1934-02	1934-09	-6.12	-42.82	7

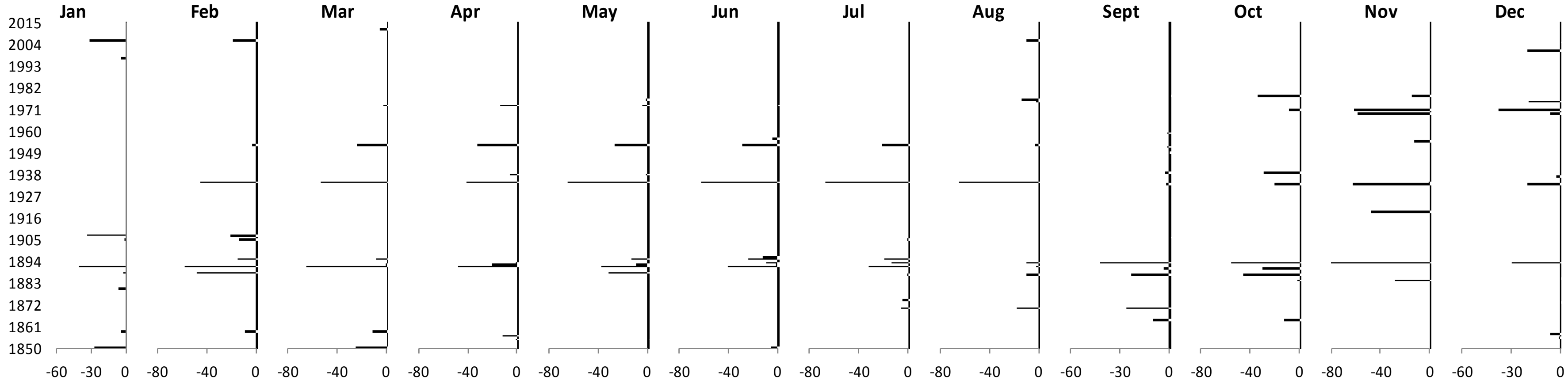
Table 5.6 Top 3 Q95 threshold droughts ranked by duration for reconstructed flows (1850-2015) for each catchment. Shown are the drought start and end dates together with the duration in months, mean low-flow Q95 deficit (m³/ s¹) and accumulated Q95 deficit (m³/ s¹)

Drought in 1933-1934 most severely affected Boyne 7012 (BFI .68) with 4 months of Q95 flow deficits from September to December 1933 and 7 months of defícts from February to August 1934. Another noteworthy drought occurred in 1953 at four catchments; Ownea 38001 (BFI.28), Ballysadare 35005 (BFI .61), Fergus 27002 (BFI .70), Owenure 26018 (BFI .72) with results showing Q95 flow deficits that persisted for 5 to 7 months. Boyne 7012 (BFI .68) experienced the largest Q95 flow deficits in 1953 and dought persisted for 8 months from February to August.

The results show that drought in 1975 and 1976 most severely affected Corock 13002 (BFI .71), Suir 16009 (BFI .63), Owenboy 19001 (BFI .68) and Brosna 25006 (BFI .71). Corock 13002 (BFI .73) experienced the longest Q95 flow deficts lasting 10 months from December 1975 to September 1976. Results indicate that the 1975/76 drought was less severe at all of the other catchments with Q95 flow deficits only lasting one to three months over the period.

Figure 5.9 and 5.10 shows the months where reconstructed flows fall below the Q95 threshold, the magnitude (x-axis) is the flow as a percentage of the long term Q95 value for that month**.** Four sample study catchments (Boyne 7012, Avonmore 10002, Ownea 38001 and Brosna 25006) were chosen and presented to provide varying catchment size and characteristics. Appendix 7 shows the results at all twelve catchments. The results suggest that the Boyne 7012 (BFI .68) was much more prone to multi season drought prior to the 1930s. The results show that the month of November at Boyne 7012 (BFI .68) has been more susceptable to severe drought. The results show that the majority of Q95 deficits in November range from -48% to a maximum deficit of -85% in 1893, a well documented drought. In addition the results show that summer drought was much more prevalent at Boyne 7012 (BFI .68) prior to 1950’s.

7012 located in the East (BFI .68)



10002 located in the Southeast (BFI .54)

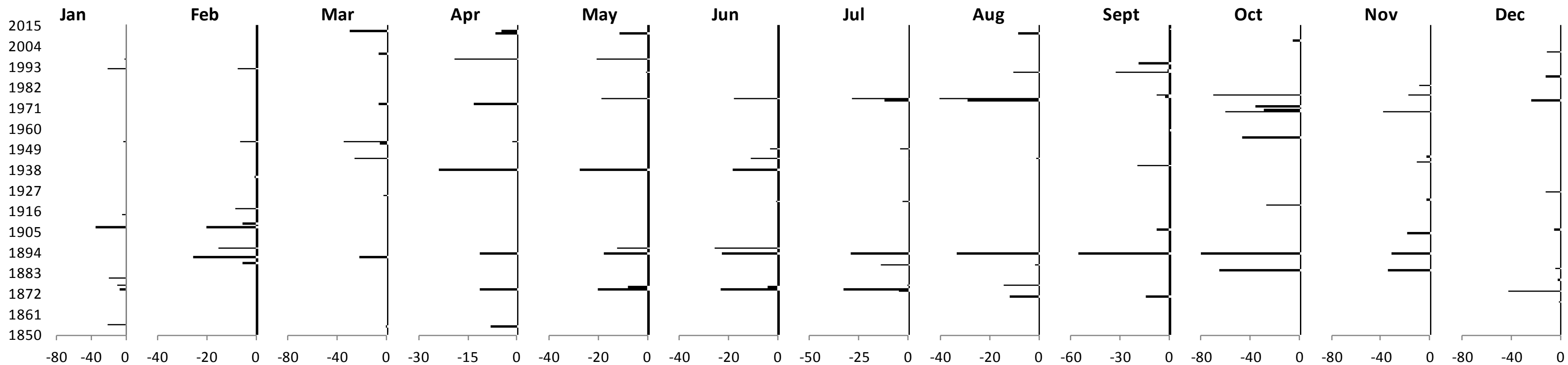
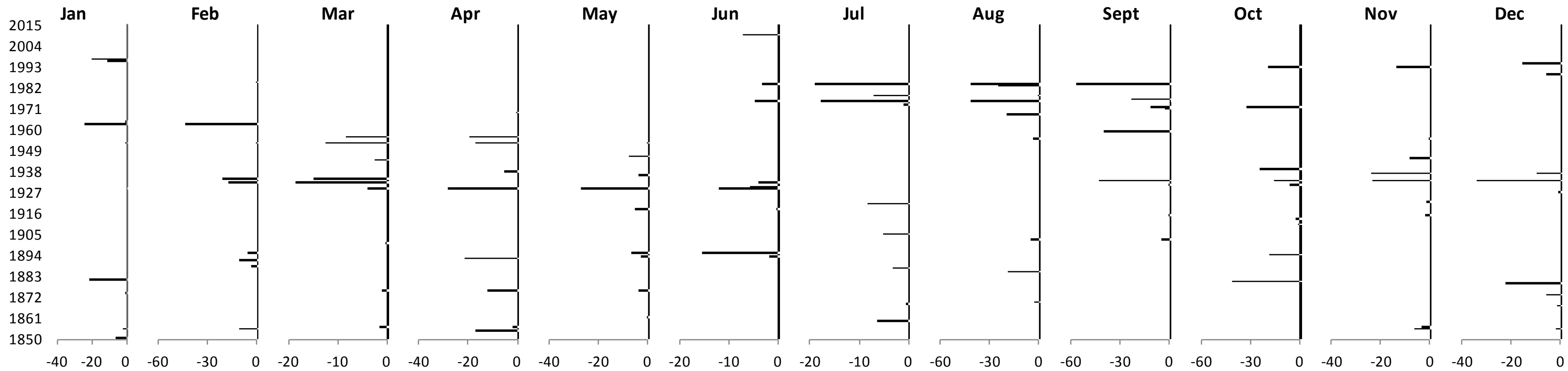


Figure 5.9 shows the months where reconstructed flows fall below the Q95 threshold at study catchments 7012 and 10002. The magnitude (x-axis) is the flow as a percentage of the long term Q95 value for that month.

38001 located in the Northwest (BFI .28)



26018 located in the West (BFI .72)

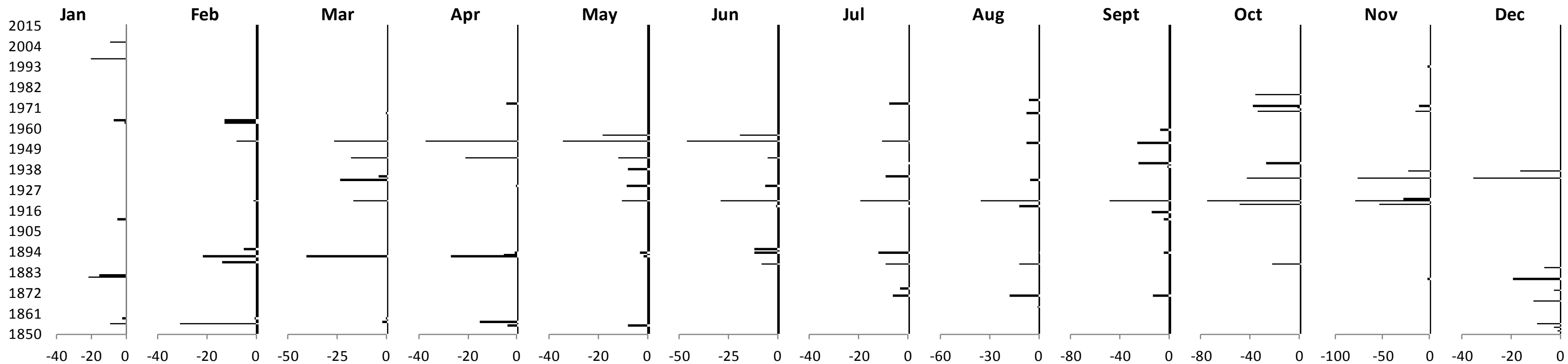


Figure 5.10 as Figure 5.9 but for study catchments 38001 and 26018.

The most notable severe drought at Avonmore10002 (BFI .54) occurred in 1893 with continous Q95 flow deficits from April-December (Figure 5.9). The maximum Q95 flow deficit of -85% was in October 1893 a month earlier than Boyne 7012 (east). The drought in 1874 at 10002 only lasted from April-August, with the largest Q95 deficit of -33% in July. During 1953 drought lasted for 4 months from January-April, but was not as severe as previous droughts with a Q95 peak deficit of -35% in March 1953. In 1976 a summer drought affected Avonmore10002 from May-August with a peak Q95 deficit of -41% in August. In recent years 10002 has also been relatively drought poor apart from 1 and 2 month Q95 deficits (e.g. 1990, 1992, 1995, 1997, 2011 and 2012). The month of October appears to be more prone to severe drought at Avonmore 10002 than other months, four of the nine drought events show Q95 deficits more than -58% .

The results (Figure 5.10) at Ownea 38001 (BFI .28) show that it was not severly affected by the drought in 1893 with only two months Q95 deficits (May and June). In 1929 a drought lasted for 4 months but the largest Q95 flow deficit only reached -28% in April. During 1933-1934 an intermittent drought occurred at Ownea 38001 (BFI .28), starting in August 1933 with some respite in January 1934 but drought resumed again February-March. The peak Q95 flow deficit -42% was found in August 1933. The drought in 1953 also affected Ownea 38001 (BFI .28) and persisted from January-May, but less severe than Boyne 7012 (BFI .68) and Avonmore 10002 (BFI .54) with Q95 deficits ranging from -0.93% to -17%. In 1963 a two month winter drought occurred (January-February) with a peak Q95 defcicit -43%. The summer drought in 1975 lasted for 3 months at Ownea 38001 (BFI .28) and reached a maximum Q95 deficit -41% in August. The most severe drought occurred in the summer 1984 persisting for 4 months, with the largest Q95 defects -57% in September 1984 Apart from some 1-2 month drought events Ownea 38001 (BFI .28) has had a drought poor period in the past 30 years. The month of September appears to be most sensitive to severe drought at Ownea 38001 (BFI .28) over the past 165 years.

The results at Brosna 25006 (BFI .72) located in the west was affected by severe drought during 1850 (Figure 5.10). The drought started in January 1850 and continued until July. Between April and September 1864 drought affected Brosna 25006 with maximum Q95 defects reaching -21% in August. A severe drought started in July 1887 lasting 9 months until March 1888 with Q95 flow deficits of -34% peaking in February 1888. Less severe drought lasting 4-5 months occcurred in 1911, 1953 and 1956 with deficits not exceeding -16% in any month. The maximum Q95 flow deficits reached -22% in April 1973. Results show Q95 flow deficits lasting 6 months in 1976 at 25006 with maximum deficts of -33% in August. In 2003 a short two month winter drought occcurred at Brosna 25006 with Q95 flow deficts of -62% in November. Another drought occurred at Brosna 25006 in the summer 2004 lasting 5 months with peak Q95 flow deficts of -24% in August. The results at Brosna 25006 suggest that November is more prone to severe drought than other months. The results also indicate that catchments with high BFI are more prone to drought later in the year.

5.4.4 Correlation between SPI and observed Q95 flow.

The development of a drought forecast method would be a valuable tool for water resource management in Ireland. The Standard Precipitation Index (SPI) is calculated by summing precipitation over specified accumulation periods (typically, 1, 3, 6, 9, 12 and 24 months) and fitting accumulation series to a parametric distribution from which probabilities are transformed to the standard normal distribution (McKee *et al.*, 1993; Guttman, 1999; Lloyd-Hughes and Saunders, 2002). SPI values give standard deviations from typical accumulated precipitation for a given location and time of year. Using four case study catchments (selected to represent a range of BFI values) this study investigates correlations (Spearmans) between SPI values for accumulation periods (1-6 months) and observed Q95 flow deficits. Observational flow data and not modelled records is used because the precipitation is used for the modelling process and this may cause misleading correlation results. The four sample catchments are; Ownea 38001, Feale 23002 (low BFI) and 12001, 7012 (high BFI). The Spearman's correlation (r_s) results for concurrent months are presented in Table 5.7 and show the SPI time scale with the strongest correlation with each monthly observed Q95 flow (results significant at the 0.05 confidence level). Spearman's correlation assesses monotonic relationships and a perfect Spearman correlation (r_s) of +1 or −1 occurs when each of the variables is a perfect monotone function of the other.

SPI-1 correlates strongest with most months at the two catchments (Ownea 38001, Feale 23002) with low BFI with r_s values for SPI-1 ranging from 0.58 to 0.94. The weakest correlations are evident for winter months. SPI-2 shows the strongest correlation with June Q95 flows (r_s = 0.70) at Ownea 38001. At Feale 23002, SPI-2 also correlates strongly with June Q95 flow (r_s = 0.71) but also with July (r_s = 0.69) and September (r_s = 0.74). SPI-3 also correlates strongly (r_s = 0.81) with August Q95 flow at Feale 23002. Stronger correlations at greater accumulations are evident for the catchments with high BFI (Boyne 7012 (BFI .68) and Scarrawalsh 12001 (BFI .72). These catchments have a high groundwater component and slower response to precipitation deficits.

	Catchment			
Month	**38001 BFI (0.28)**	**23002 BFI (0.31)**	**7012 BFI (0.68)**	**12001 BFI(0.72)**
Jan	SPI-1	SPI-1	SPI-2	SPI-1
	0.74	**0.90**	**0.82**	**0.62**
Feb	SPI-1	SPI-1	SPI-2	SPI-1
	0.94	**0.87**	**0.78**	**0.80**
Mar	SPI-1	SPI-1	SPI-2	SPI-2
	0.85	**0.75**	**0.80**	**0.70**
Apr	SPI-1	SPI-1	SPI-2	SPI-2
	0.92	**0.69**	**0.80**	**0.75**
May	SPI-1	SPI-1	SPI-2	SPI-2
	0.89	**0.69**	**0.77**	**0.74**
Jun	SPI-2	SPI-2	SPI-4	SPI-3
	0.70	**0.71**	**0.84**	**0.65**
Jul	SPI-1	SPI-2	SPI-3	SPI-4
	0.58	**0.69**	**0.78**	**0.69**
Aug	SPI-1	SPI-3	SPI-4	SPI-5
	0.83	**0.81**	**0.79**	**0.67**
Sep	SPI-1	SPI-2	SPI-3	SPI-5
	0.80	**0.74**	**0.85**	**0.81**
Oct	SPI-1	SPI-1	SPI-6	SPI-3
	0.94	**0.77**	**0.76**	**0.80**
Nov	SPI-1	SPI-1	SPI-2	SPI-4
	0.88	**0.83**	**0.79**	**0.82**
Dec	SPI-1	SPI-1	SPI-2	SPI-2
	0.86	**0.82**	**0.83**	**0.72**

Table 5.7 Spearman's correlation (r_s) results (highlighted in bold) between observed Q95 river flows at each catchment and the SPI values of different accumulations for corresponding rainfall station. Only the SPI accumulation with strongest correlation is shown, The base flow index for gauges at each catchment is also presented as BFI. All results are significant at the 0.05 confidence level.

Results for Boyne 7012 (BFI 0.68) indicate that SPI-2 is strongly correlated with most of the winter and spring monthly Q95 flows. SPI-3 is strongly correlated with Q95 flow at Boyne 7012 for July (r_s = 0.78) and September r_s = 0.85. SPI-4 shows a strong relationship with June (r_s = 0.84) and August (r_s = 0.79). Results also indicate that SPI-6 strongly correlates with October (r_s = 0.76) Q95 flow at Boyne 7012 (BFI .68). The results (Table 5.7) for Scarrawalsh 12001 (BFI 0.72) show that SPI-2 strongly correlates with monthly Q95 flows for March (r_s = 0.70), April (r_s = 0.75), May (r_s = 0.74) and December (r_s = 0.83). SPI-3 shows a strong relationship with Scarrawalsh 12001 Q95 flow for June (r_s = 0.65) and October (r_s = 0.80) while SPI-4 correlates strongly with July (r_s = 0.69) and November (r_s = 0.82) Q95. SPI-5 shows a strong correlation with 12001 Q95 flow for August (r_s = 0.67). As expected, stronger correlations with Q95 flows are found for longer accumulations of SPI in groundwater dominated catchment. In addition, the strong correlations indicate potential to use SPI of varying accumulations as an estimate of drought severity at ungauged locations once catchment characteristics such as BFI are known. This is an important area for future work.

To determine if there is a lagged relationship between SPI (accumulation periods 1-6 month) and the observed Q95 anomalies correlations were calculated for the observed Q95 flow lagged by 0 to 5 months after the SPI series. The results are presented in Figure 5.11 and indicate only weak lagged relationships in the catchments with low BFI (i.e. runoff dominated catchment). In all cases when investigating lagged relationships there is a large drop from concurrent correlations with correlations decreasing for longer duration lags. However, results at the two groundwater dominated catchments with high BFI (Boyne 7012 and Scarrawalsh 12001) show more promise for use as a drought forecasting tool. Interestingly, at Boyne 7012 the SPI at 1-3 accumulation periods strongly correlate with Boyne 7012 Q95 anomalies with 1 month lag indicating correlations greater than 0.40. The results also show useful but slightly weaker correlations for SPI-4 and SPI-5 and Q95 anomalies at 1 month lag with correlations of 0.36 and 0.33 respectively (Figure 5.11). At longer than one month lags only weak correlations are evident, for example for SPI-1 and SPI-2 at 2 month lag results range from 0.17 to 0.20. Results at Scarrawalsh 12001 are similar to Boyne 7012. The SPI-1 and SPI-2 accumulations show strong correlations with Q95 flow at 1 month lag with r_s values of 0.45 and 0.41 respectively. Results also show that SPI-3 and SPI-4 and Q95 anomalies 1 month lag have slightly weaker by useful correlation values greater than 0.33. Surprisingly, results indicate that SPI-1 correlates with Q95 flow at up to 3 months lag with a correlation of 0.29. Overall, for the catchments with high BFI values results indicate that there is potential to use SPI of varying accumulations for forecasting Q95. Lagged predictive relationships tend to be greatest at one month lag but potentially useful results are evident at longer ranges.

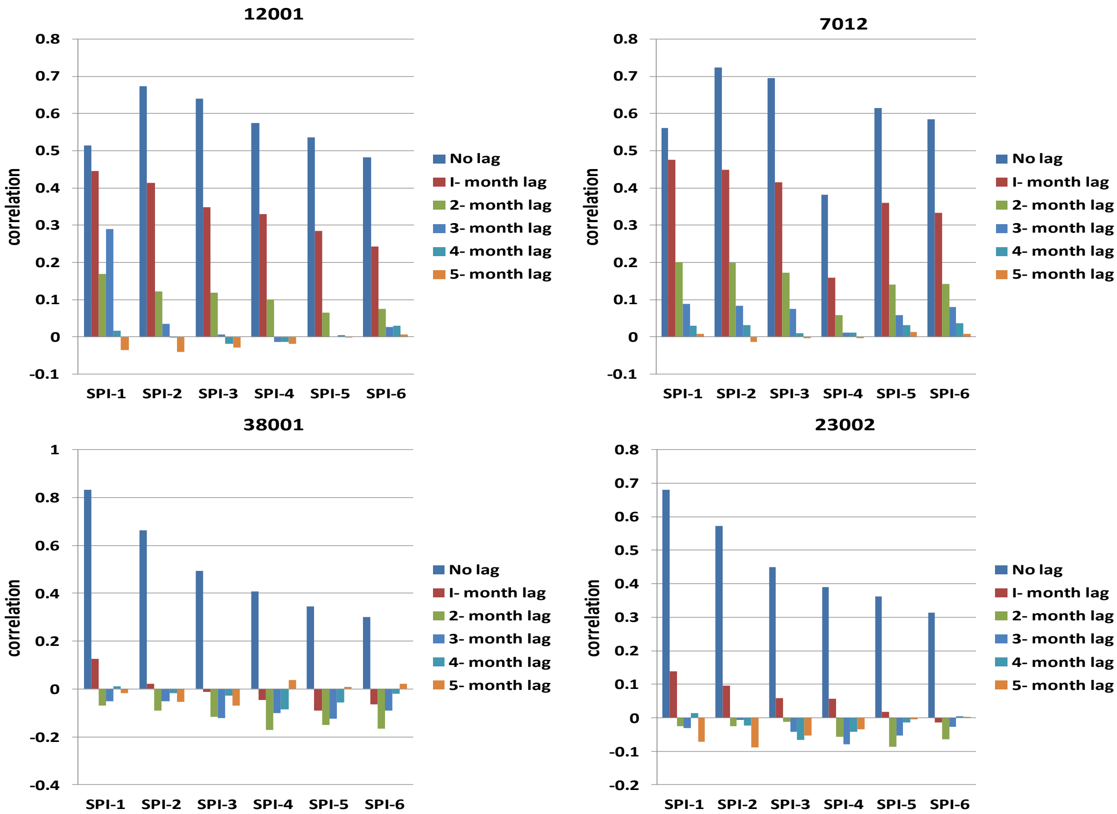


Figure 5.11 Concurrent and lagged correlation results between SPI (1-6 month accumulations and the observed Q95 flow at four study catchments.

5.4.5 Seasonal correlation between NAO and reconstructed flows.

Finally, the study investigated the influence of the seasonal NAO on Irish river flow. The reconstructed flows at each catchment were consolidated into seasonal mean flows; winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Correlations are evaluated with the NAO index for concurrent seasons and lagged relationships between summer flow and previous winter NAO is also investigated. All the correlation results reported are significant at the 0.05 level. The analysis is constrained to the period 1866-2015 given the availability of NAO index data over this time period. Correlations are evaluated using Spearman's correlation (r_s). Results are presented in Table 5.8 where values highlighted in blue are significant at the 0.05 level and those in red are significant at the 0.01 level. Figure 5.12 maps the correlations across catchments.

Catchment	Winter NAO-Flow	Spring NAO-Flow	Summer NAO-Flow	Autumn NAO-Flow	Winter NAO-Summer Flow
38001	**0.475**	**0.322**	0.062	**0.461**	-0.017
35005	**0.463**	**0.279**	-0.038	**0.394**	-0.071
27002	**0.428**	**0.224**	0.026	**0.324**	-0.094
26018	**0.341**	**0.240**	-0.065	**0.290**	-0.108
25006	**0.309**	**0.171**	-0.013	**0.273**	-0.072
23002	**0.457**	**0.207**	0.001	**0.356**	-0.087
19001	-0.057	0.042	-0.086	-0.004	-0.119
16009	-0.052	0.130	-0.040	0.129	-0.066
13002	-0.087	-0.02	-0.032	0.043	-0.120
12001	-0.089	0.060	-0.066	0.020	**-0.166**
10002	-0.126	0.025	-0.068	0.074	-0.070
7012	0.129	0.104	-0.002	0.188	-0.115

Table 5.8 presents the correlation (r_s) results between the seasonal reconstructed flow 1866-2015 and the seasonal NAO index (1866-2015). The fifth column shows the correlation results between summer mean flow and previous winter NAO. Values highlighted in (blue) are significant at the 0.01 level and those in (red) are significant at the 0.05 level.

For winter NAO and winter mean flow r_s values range from -0.087 to 0.475. Strongest correlation (r_s = 0.475) was found with winter mean flows at Ownea 38001. Strong winter correlations are also evident for Fergus 27002 and Ballysadare 35005 (both 0.01 level) with r_s coefficients of 0.463 and 0.428 respectively. Outside of catchments in the west and northwest only weak correlations are evident. Spring mean flows and spring NAO show r_s values ranging from 0.02 to 0.322. Largest correlations are also at 38001 (r_s = 0.322; 0.01 level), while catchments Owenure 26018, Fergus 27002 and Ballysadare 35005 all show significant correlations greater than (r_s = 0.22; 0.01 level).

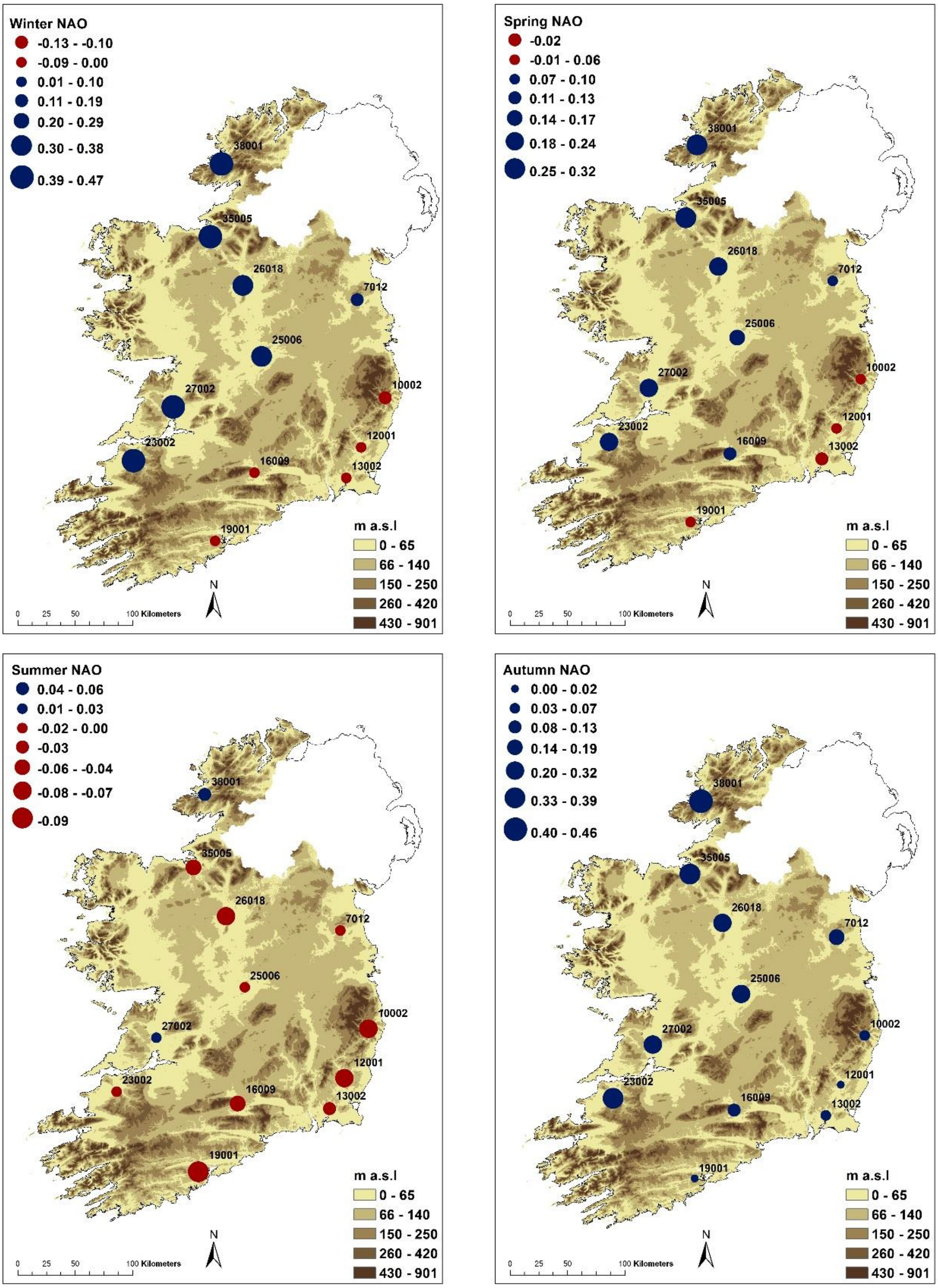


Figure 5.12 Correlation results between seasonal mean flow and the seasonal NAO. The blue circles represent positive r_s correlation results, red circles represent negative r_s correlation results. Size of circle represents the magnitude of the correlation (small to large)

Weaker correlations, though still significant, are evident between spring mean flow and spring NAO at Feale 23002 (r_s = 0.207; 0.05 level) and Brosna 25006 (r_s = 0.171; 0.05level). For summer mean flows no significant correlations with summer NAO are found at all catchments. For autumn mean flows significant correlations with concurrent autumn NAO are weak and again constrained to catchments along western and north western margins. The largest significant correlation for autumn is found at Ownea 38001 (r_s = 0.46; 0.01 level). The correlation results between summer mean flow and previous winter NAO show no significant correlations with the exception of catchment Scarrawalsh 12001 where a negative correlation (r_s = -0.17; 0.05 level) is evident. Again this catchment has a high BFI and thus groundwater may provide a longer term catchment memory. Interestingly other catchments with high BFI in other locations do not show this relationship.

5.5 Discussion

This chapter has reconstructed river flow at twelve Irish catchments for the period 1850-2015. These catchments were selected to provide good spatial coverage and to incorporate diverse catchment characteristics. Homogenous long-term monthly precipitation records and long-term average PET data were used to the run the conceptual rainfall runoff model HYSIM to reconstruct river flows. However, there are some limitations in reconstructing river flows. It has to be assumed that land use remains constant over the time period; any changes would impact on the flow regime. Due to a lack of long-term temperature records this study was unable to simulate the impacts of snow melt on the winter flows. Furthermore, this study used LTA PET because of the lack of long-term observed PET and temperature records.

Two drought indices were employed to identify drought in each catchment. The different drought indices provide an overview of historical Irish drought ranging from deficits (DSI) to extreme drought events that exceed long term Q95 thresholds. For each catchment tables of historical drought using both Q95 flows and the DSI indices showing the start and end of drought, mean and accumulated flow deficits along with drought duration are provided (Appendix 4 and 5). The most noteworthy drought years based on the top ten ranked Q95 and DSI droughts are as follows: 1855-1860, 1887-1888, 1891-1894, 1902-1912, 1933-1934, 1953, 1971-1976.

Chapter 4 identified 7 meteorological drought rich periods from the IIP network using SPI. The same study used historical documentary evidence to provide details of the socio economic impacts, while adding confidence in the results. The drought period was defined as years in which at least 40% of the stations in the IIP network experience events of at least 18 months duration. The hydrological droughts identified in this study are much shorter than the meteorological drought identified in Chapter 4 and is most like due to influence of groundwater in catchments with higher BFI. In addition, different drought indices are used. Chapter 4 used SPI-12 which calculates 12 month accumulated deficits whereas this study calculates monthly Q95 and DSI deficits.

The key DSI relative to the 1961-1990 baseline results indicate that some long duration drought was experienced at the twelve study catchments (Table 5.6 and Appendix 4). Most notable is the periods were 1854-1858 and 1887-1888 when drought affected all catchments, with some catchments experiencing up to 22 months of drought. Catchments with high BFI located in the south, midlands, southeast and east (e.g. Brosna 25006, Owenboy 19001, Suir 16009, Corock 13002, Scarrawalsh 12001, and Boyne 7012) appear to have been more severely affected by drought during periods of long duration precipitation deficits as shown in Chapter 4 (e.g. 1854-1860, 1884-1896, 1904-1912, 1933-1934 and 1969-1977). This is due to these catchments being reliant on winter rainfall for recharging the groundwater component and as such the longer drought periods impact on this recharge. In contrast Feale 23002 (BFI .31) located in the west and Ownea 38001 (BFI .28) in the northwest appear to have been less severely affected by drought since 1850. Both these catchments results show that both duration and DSI accumulated deficits are the lowest when compared to other catchments during drought periods.

The DSI 12 month running mean relative to the 1961-1990 baseline highlights the temporal and spatial diversity of Irish droughts (Figure 5.8 and Appendix 5). Similar to Chapter 4 the DSI 12 month mean deficit results of this study also show a prolonged drought lasting up to 80 months during 1854-1860 at most study catchments (Appendix 5). During the period 1884-1895 the continuous mean DSI deficits ranged from 120 months at Ballysadare 35005 (BFI .61) located in the west, to 24 months at Corock 13002 (BFI .73) in the southeast. During 1902-1910 DSI 12 month mean deficits persisted for 87 months at Scarrawalsh 12001 (BFI .72) in the southeast and 76 months at Owenboy19001 (BFI .68) in the south. Drought was identified during 1933-1936 which affected most catchments except those located in the midlands and northwest.

Flows below Q95 represent the most severe drought events. Results show that during 1854-1860 most catchments experienced drought lasting up to 4 months. The results highlight the spatial diversity of drought in Ireland for example the drought in 1887 mainly affected catchments located in the south, southeast, southwest and midlands. The temporal extent of the 1887 drought ranged from 6 to 9 months. Another notable severe drought occurred during 1893-1894 lasting between 4 and 9 months at all catchments. Drought 1893-1894 catchments located in the southwest, southeast and east were worst affected by drought where extreme low flows lasted up to 9 months. Only two study catchments at Boyne 7012 (BFI .68) located in the east and Brosna 25006 (BFI .71) in the midlands were affected by a drought in 1953 for 6 months. The majority of catchments were affected by drought during the 1970's with the longest Q95 drought lasting up to 10 months during 1975-1976 at catchment Corock 13002 BFI .73) in the southeast. The Q95 flow deficit results also highlight that Boyne 7012 (BFI .68), Corock 13002 (BFI .73), Scarrawalsh 12001 (BFI .72), and Brosna 25006 (BFI .71) located in the east, south and southeast appear to be have been more prone to severe drought over the past 165 years. During the periods of long duration precipitation deficits identified in Chapter 4 these catchments with high BFI reached Q95 deficits as high as -85%. These results suggest that catchment with groundwater dominated flow are less responsive until the storage is depleted due to long duration precipitation deficits. In contrast the Q95 flow deficits results indicate that catchments with a low BFI such as the Feale 23002 (BFI .31) and Ownea 38001 (BFI .28) were less severely affected by drought since 1850.

The 1995 drought was analysed from a water management perspective by Mac Cárthaigh (1996) and is currently used as a benchmark for Irish infrastructure and water resource plans. The 1995 drought does not feature in the ranked top ten Q95 flow or DSI results with more severe droughts identified during the 19^{th} Century. The past 40 years appear to have been a relatively drought poor period. Therefore, the results presented in this chapter provide important information about historical hydrological drought which could be integrated into Irish water management plans. The Q95 results indicate that catchments located in the south, east and southeast have been more prone to severe drought in the past. Therefore, if future drought similar to those experienced in the past occurred it would have serious implications for water supply as the majority of Ireland's population live in the south, east and southeast.

The identified drought periods in this study show good coherence with studies conducted in the UK, which highlights the large spatial extent of some of the historical droughts. Lennard *et al.* (2015) showed drought periods occurred at rivers in the UK and Wales during 1887-1889, 1892-1897, 1933-1934 and 1975-1976, which closely correspond to droughts identified in this study. Other work in UK (e.g. Jones *et al.,* 2006; Marsh *et al.,* 2006; Todd *et al.,* 2013; Spraggs *et al.,* 2015) also identified severe drought periods across the UK that agree with the results of this study. The consistency with previous work builds confidence in the reconstructed flows and the subsequent results.

The correlation between different SPI accumulation periods and the Q95 flow for each month show interesting initial results (Table 5.8). SPI with shorter accumulation periods (SPI-1, SPI-2) has the strongest correlation with Q95 flow at catchments with low BFI. However, longer SPI accumulation periods such as SPI-3 to SPI-6 strongly correlate with Q95 flows in catchments with high BFI. The results show that different SPI accumulation periods correlate with specific months, for example SPI-4 correlates strongest with June Q95, but SPI-6 strongly correlates with August Q95 at Boyne 7012. At Scarrawalsh12001 SPI-4 correlates the strongest with Q95 in July and SPI-5 strongly correlates with Q95 during September. The identification of these monthly relationships provides a potential method to estimate monthly low flows for catchments where no records exist. The method could firstly identify ungauged catchment characteristics and using the relationships between SPI and Q95 calculate SPI from available precipitation records and estimate monthly river flow conditions.

The correlation results between SPI (1-6 accumulation periods) and Q95 flow at 0 to 5 month lags show some interesting results for groundwater dominated catchments (high BFI). The initial results at two study catchments (Scarrawalsh 12001 and Boyne 7012) with higher BFI suggest that SPI has some potential utility as a river flow drought forecasting tool (Figure 5.9). The results indicate that SPI accumulation time periods 1-3 months are strongly correlated with Q95 flow at lags of between 1 and 2 months. Barker *et al.* (2015) found that lagged SPI over several months has the potential for early warning of hydrological drought. These results are similar to those found in Wang *et al.* (2015) and Du *et al.* (2013) who found high correlations with various SPI time scales, but note that SPI-2 showed the most potential for identifying and for monitoring drought. The results of this chapter demonstrate that need of future research to prioritise future work to expand the study catchments and investigate using the SPI as a drought forecasting tool.

In addition, the SPI values are normalized so wetter climates across a region can also be represented and monitored in the same way as dry spells (Sieler *et al.*, 2002; WMO, 2012; Du *et al.*, 2013). Bordi *et al.* (2007) used the SPI to identify extreme monthly wet and dry spells across Sicily. Piccarreta *et al.* (2004) also employed the SPI and identified nine well defined wet cycles in monthly precipitation records 1923-2000, related to major flood events for southern Italy. Sieler *et al.* (2002) applied the SPI to monthly precipitation across the Cordoba region in Argentina and results explain the development of conditions leading up to three main flood events, and suggest SPI as an effective tool for climate risk monitoring (Seiler *et al.*, 2002). Similarly, future work in Ireland could also investigate using SPI to identify historical wet periods and the potential for monitoring high flows.

Seasonal mean flow and seasonal NAO correlations indicate that winter, spring and autumn flow at catchments located in the southwest, west, midlands and northwest are significantly correlated with the winter, spring and autumn NAO. Ownea 38001 (BFI .28) located in the northwest has the strongest correlation with winter, spring and autumn NAO. Ownea 38001 has the lowest BFI (runoff dominated) of all the study catchments and a mean catchment elevation of 185 metres above sea level (m.a.s.l). Feale 23002 (BFI .31) is also a runoff dominated catchment located in the southwest (196 m.a.s.l) and shows a strong correlation with winter, spring and autumn NAO. This would suggest a link between catchments characteristics and NAO. However, the other five catchments (Ballysadare 35005, Fergus 27002, Owenure 26018, Brosna 25006, and Feale 23002) strongly correlated with the NAO are all located in areas of lower elevations (> 100 m.a.s.l) and have groundwater dominated flow. These results are similar to Harrigan (2016) who found that catchments at lower elevation (< 100 m.a.s.l) with high BFI have the strongest correlations with NAO.

5.6 Chapter conclusion

This chapter has addressed **thesis objective 5** by using the homogenous long-term monthly precipitation produced by this thesis to reconstruct river flows at selected Irish catchments for the period 1850-2015. The reconstructed flows were analysed to identify historical hydrological drought. Results identified seven major hydrological drought periods which affected the majority of study catchments. These periods also correspond with previous work in the UK and corroborate findings using rainfall in previous chapters, thus adding confidence to the reconstructions. This chapter has also revealed the potential for future work to produce a forecasting tool for drought in Irish river flows using the SPI. Chapter results have also provided important information that is crucial for water resource management in Ireland. The next chapter will focus on an overarching discussion.

6 Discussion, limitations and future work

6.1 Introduction

This chapter aims to provide a synthesis of the key thesis themes while emphasising the value of long-term records, metadata, and documentary evidence. This chapter will also discuss research limitations and identify priorities for future research.

6.2 Synthesis of key themes

This research conducted in the thesis has presented important insights into the past climate in Ireland and provided essential information on changes in precipitation over the past 165 years. This thesis has produced a quality assured long-term monthly precipitation at 25 stations for the island of Ireland 1850-2015 which is only second in longevity to the England and Wales Precipitation series (EWP) (Alexander and Jones, 2001). This research has also some significant implications, as results have shown that Ireland has been prone to periods of severe and prolonged drought in the past. Impacts from severe drought periods included reduced or failed crop yields, increased agricultural produce prices, human health issues and livestock deaths, water restrictions, low reservoir levels, water supply failures and hydro-power reductions. The drought in 1854-1860 lasted over 70 months across many parts of Ireland and a key question that should be explored is how would current water supply infrastructure cope with a drought of this type?

In addition, the data produced by this thesis is openly available for future analysis and has led to further research, which I was co-author and the subsequent work has further added to the knowledge of past climate in this region. Wilby *et al.* (2015) examined persistent meteorological drought using the homogenous network of 25 precipitation stations 1850-2010 (produced by this thesis) the study first calculated the mean monthly precipitation, with averages combined into mean winter half year (October-March) and summer half year (April-September). The seasonal anomalies for the 1850-2010 series were then calculated relative to the 1961-1990 baseline (Wilby *et al.*, 2015). The below average precipitation from each half year was identified, with a widespread event defined when more than two thirds of the 25 stations showed a dry season. Results identified periods of prolonged dry spells with stations across the southeast and east having experienced up to 5 years persistent below average rainfall when compared with the 1961-1990 baseline, or

3 years below average across the whole series (Wilby *et al.*, 2015). Most notable persistent dry spell events were identified during 1853-1856, 1886-1888, 1892-1894 and 1970-1973 which all correspond with the results of Chapter 4 in this thesis. Further results using the Markov dry spell simulations show that the likelihood of a 5-year dry spell at Dublin is very high (p=0.125) with near unbroken 10 year runs or more plausible (Wilby *et al.*, 2015). Murphy *et al.* (2016) found some interesting information on social economic impacts and past societal responses to drought, this work stemmed from the documentary evidence source material accessed in Chapter 4 of this thesis. The paper presents some interesting historical and cultural insights into how drought in the past affected past society.

The IIP 25 station network produced from this thesis has also been utilised in a recent study by Matthews *et al.* (2016) which also presents important insights into changes in the climate in this region. The study examined the changing likelihood of extreme seasonal conditions in the long-term observation records and explored how frequent these extremes might occur in the future using the latest model projections (Matthews *et al.*, 2016). The results indicate that the likelihood of the wettest winter (1994/95) and driest summer (1995) occurring has doubled since 1850 respectively (Matthews *et al.*, 2016). The results also show that the most severe end-of-century climate model projections indicate that the occurrence of wet winters like 1994/95 and summers as dry as 1995 may increase by factors of 8 and 10 respectively by the end of the century (Matthews *et al.*, 2016). The IIP precipitation network has also been integrated into Maynooth University postgraduate teaching modules to give students experience in dealing with long-term datasets.

6.2.1 Value of long-term good quality observations

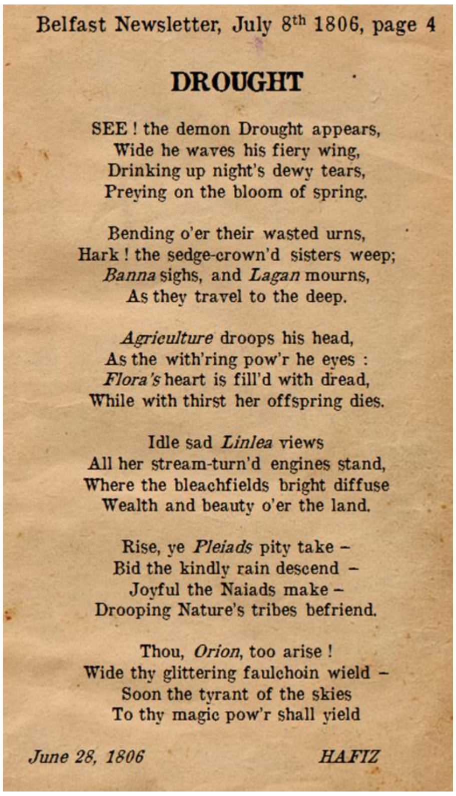
A key theme throughout this thesis is the importance of long-term records. However, as highlighted in Chapter 3 many issues can arise with historical meteorological records, such as instrumental changes, gauge or station moves, faulty instruments, influence from vegetation or recording errors. This thesis employed HOMER software to check the long-term monthly precipitation records for homogeneity and all detected breaks were checked by scrutinising the metadata and then adjusted accordingly. In producing a quality assured monthly precipitation 25 station network 1850-2015 for Ireland this thesis has addressed a major research gap for this region. This research has highlighted the importance of long-term observations in understanding changes in precipitation over the long-term and highlights past monthly and seasonal extremes. The results of Chapter 3 show that trends post 1940 were in some cases opposite to the trends detected over the long-term, which highlights the importance of long records. Moreover, this work offers rich opportunities to understand long-term variability at the scale of the British-Irish Isles - a sentinel maritime location on Europe's Atlantic coast.

6.2.2 Value of metadata

Another key thesis theme is the value of station metadata. This work has demonstrated the importance of metadata when conducted quality checks, homogeneity tests and subsequent climate analysis. In data homogenisation testing detailed metadata and station history are critical in evaluating identified breaks; otherwise correcting issues within the records is not an informed decision. Metadata can provide the location of station instruments, when and how observations were recorded, important notes on instrument changes and faults or environmental changes such as vegetation encroachment at the site or site moves. This thesis has produced an invaluable eighteen-page detailed metadata file which was compiled from six different sources and is also openly available for future research to use. I encourage that this be the standard practice in all homogenisation studies.

6.2.3 Value of documentary evidence

In addition, Chapter 4 identified and integrated documentary evidence into the quantitative drought analysis. Documentary sources, primarily newspaper archives, are a significant resource for verifying quantitative analysis of drought from long–term precipitation records. Ireland has some of the longest running newspapers in the world. Of particular note are the *Belfast Newsletter* (the world's oldest continuously published newspaper) and the *Freeman's Journal* which began reporting in the early and mid-18th Century respectively. A further nine titles commenced in the 19th Century, with many of these titles continuing to the present day. These resources provide a rare insight into the occurrence and impacts of drought over the same period. Beyond data assurance these documentary sources reveal insights to cultural responses to droughts. In searching these archives chapter 4 discovered hundreds of articles referring to many different droughts, including several remarkable drought episodes. These articles communicated important aspects of significant droughts in the 19th Century. For example, the period September 1800 to January 1809 was one of the most persistent drought episodes of the past 250 years. Several reports in the *Freeman's Journal* describe potato crop failure and highlight that the woollen industry declined in 1802 due to lack of water to work the mills. Other newspapers of the time report a severe drought period across the UK and Europe during 1800-1809 with descriptions of poor crop growth and livestock dying. On the 8th July 1806, a poem appeared in the *Belfast Newsletter* simply entitled 'Drought' signed by HAFIZ and was written on the 28th June 1806 (Figure 6.1). It provides a powerful depiction of the devastating impact of drought, with the tone and language pleading for reprieve from the "demon" drought.



Belfast Newsletter, July 8th 1806, page 4

DROUGHT

SEE ! the demon Drought appears,
Wide he waves his fiery wing,
Drinking up night's dewy tears,
Preying on the bloom of spring.

Bending o'er their wasted urns,
Hark ! the sedge-crown'd sisters weep;
Banna sighs, and *Lagan* mourns,
As they travel to the deep.

Agriculture droops his head,
As the with'ring pow'r he eyes :
Flora's heart is fill'd with dread,
While with thirst her offspring dies.

Idle sad *Linlea* views
All her stream-turn'd engines stand,
Where the bleachfields bright diffuse
Wealth and beauty o'er the land.

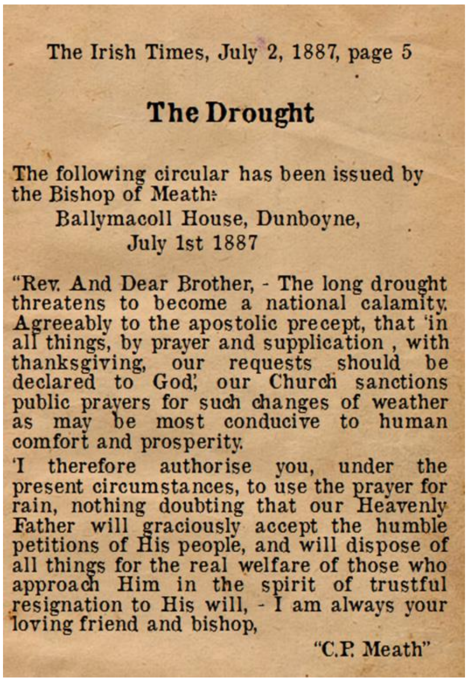
Rise, ye *Pleiads* pity take –
Bid the kindly rain descend –
Joyful the Naiads make –
Drooping Nature's tribes befriend.

Thou, *Orion*, too arise !
Wide thy glittering faulchoin wield –
Soon the tyrant of the skies
To thy magic pow'r shall yield

June 28, 1806 *HAFIZ*

Figure 6.1 The poem "Drought" which appeared in the Belfast Newsletter on the 28th June 1806

The island-wide drought of 1887 was one of the most severe droughts experienced in the last 250 years (Noone *et al.*, 2016). Chapter 4 shows that the 1887 drought was the most intense in the east of the country leading to widespread crop failures, water supply issues and public health concerns due to a lack of water to flush the sewers. By summer 1887, a circular entitled '*The Drought*' issued by the Bishop of Meath appeared in the *Irish Times* on July 2nd and authorised the faithful to pray for rain (Figure 6.2). Such a response provides a glimpse into the desperation that must have been felt across society. As far as this study knows, this is the only public call for drought-relief by prayer in the 250 years of the Irish newspaper archive.



The Irish Times, July 2, 1887, page 5

The Drought

The following circular has been issued by the Bishop of Meath:

Ballymacoll House, Dunboyne,
July 1st 1887

"Rev. And Dear Brother, - The long drought threatens to become a national calamity. Agreeably to the apostolic precept, that 'in all things, by prayer and supplication , with thanksgiving, our requests should be declared to God,' our Church sanctions public prayers for such changes of weather as may be most conducive to human comfort and prosperity.

'I therefore authorise you, under the present circumstances, to use the prayer for rain, nothing doubting that our Heavenly Father will graciously accept the humble petitions of His people, and will dispose of all things for the real welfare of those who approach Him in the spirit of trustful resignation to His will, - I am always your loving friend and bishop,

"C.P. Meath"

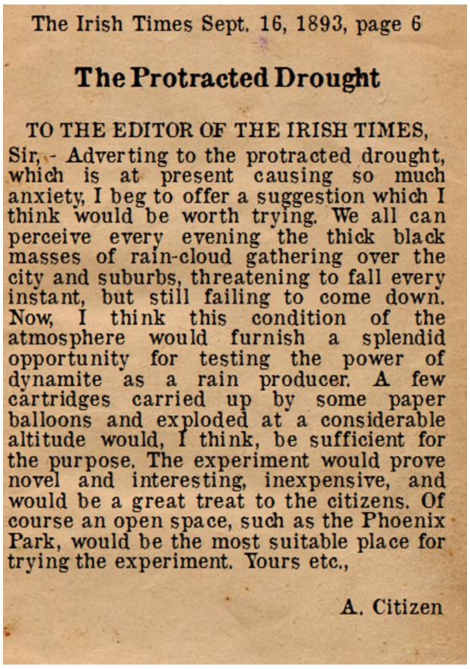
Figure 6.2 Circular from the Bishop of Meath authorising the prayer for rain. Published in the Irish Times on 2nd July 1887.

An extreme drought event began in spring 1893 that more severely affected the east and southeast of Ireland. By autumn the drought caused a severe water supply crisis for Dublin city. The *Freeman's Journal* states on the 27th April 1893 that "*there has been an absolute drought since March 5th - for fifty two days*". The article then quotes Mr. Symons, the eminent English Meteorologist, who said that "*this is by far the longest period during which dry conditions have prevailed*" since he began making observations in 1857. On the 5th September 1893, the *Freeman's Journal* reported that "*the great drought of the present season has reduced the water supply of the city to such an extent that the greatest care and economy will be required on the part of the citizens to avert the calamity of a water famine*".

By October Dublin could only rely on 16 days of supply from the Vartry reservoir. The *Irish Times* also reported that many parts of Dublin city experienced intermittent water supplies that were delivered between 10pm and 10am at the request of local bakeries. Reports in the *Irish Times* on 30th June and 21st July 1887 describe how residents spoke of the foul smell from city sewers and feared disease due to a lack of water to flush the waste.

The crisis of water supply in 1887 caused debate within the media and academic circles around the primary cause of failure and potential solutions. In March 1894, a paper was given in the Statistical and Social Inquiry Society of Ireland entitled '*Our Present and Future Water Supply*' by John A. Walker, chairman of the Dublin Waterworks committee. Walker (1894) argued that the drought was exacerbated by an expansion of the area supplied by the Vartry reservoir, beyond the initial design assumptions, to suburban areas of the city where wastage among wealthy households was seen as profligate (Walker, 1894). This view was supported by others in the audience as recounted the following day in the *Irish Times* (14^{th} March 1894: 7).

The drought and subsequent water supply crisis in 1893 obviously left a major impression on the public imagination. The city was facing intermittent supplies and water restrictions, so one member of the public wrote to the *Irish Times* on the 16th September 1893 about 'The Protracted Drought' and made a daring suggestion (Figure 6.3).



The Irish Times Sept. 16, 1893, page 6

The Protracted Drought

TO THE EDITOR OF THE IRISH TIMES,

Sir, - Adverting to the protracted drought, which is at present causing so much anxiety, I beg to offer a suggestion which I think would be worth trying. We all can perceive every evening the thick black masses of rain-cloud gathering over the city and suburbs, threatening to fall every instant, but still failing to come down. Now, I think this condition of the atmosphere would furnish a splendid opportunity for testing the power of dynamite as a rain producer. A few cartridges carried up by some paper balloons and exploded at a considerable altitude would, I think, be sufficient for the purpose. The experiment would prove novel and interesting, inexpensive, and would be a great treat to the citizens. Of course an open space, such as the Phoenix Park, would be the most suitable place for trying the experiment. Yours etc.,

A. Citizen

Figure 6.3 Letter to the Irish Times published 16th September 1893 proposing exploding dynamite over Dublin to try and induce rainfall.

The letter, (signed A. Citizen) recommends a weather modification experiment to bring an end to the drought. The letter suggests exploding dynamite above the city to urge the obvious clouds to give up their moisture. As the author claims, this experiment would indeed have proved novel, if in the end unlikely to alter the course of events.

Recollections of past extremes can play a role in building resilience to future events (McEwen and Jones, 2012). The paucity of notable recent droughts also highlights the value of recalling past events from media archives. Newspapers provide an important source of such information that can be cross-referenced with other neighbouring, drought catalogues (e.g. Marsh *et al*., 2007). As shown in this study, Ireland has rich newspaper archives that contain interesting eye-witness accounts of how drought can impact society. It is hoped that this study will serve to remind that Ireland is, despite recent experience, surprisingly drought prone.

6.3 Broader context of this research and why it is important.

The research conducted in this thesis has produced 165 years of homogenous long-term precipitation records at 25 stations across the island of Ireland. In doing so this research has contributed to the aims of several Global data rescue initiatives (e.g. WMO, IEDRO, ISTI, ACRE). This study is also strongly aligned with the principles of Global data initiatives in recognising the value of rescuing and digitising hard copy weather records. The dedication of observers in keeping these records is commendable and in many cases has been a lifetime's work. Therefore, as scientists we have an obligation to secure these records ensuring that the data can be used in the future by making them available to the wider scientific community. Moreover, the historical documentary information presented in this study provides a clearer understanding of the impacts that past extremes have had on society.

The methods employed by this study are also transferable to other regions that have limited long-term records but where hard copy records exist. This study has presented methods of data rescue, data bridging, transcribing and quality assurance. This has been the first study to apply HOMER homogenisation software to long-term monthly precipitation data. The results indicate that HOMER performed well and identified non-climatic breaks in the long-term precipitation records. The integration of metadata into the homogenisation process has proven to be crucial in assessing the breaks detected by HOMER.

Recent decades have been conspicuously drought free in Ireland and more importantly most recent experiences of protracted drought are based on the mid-1970s. Although short, sharp droughts occurred in the summers of 1995, 2006 and 2013 these events are in no way comparable to the long and intense droughts of earlier centuries. This raises questions about whether the underlying causes of long droughts in Ireland have changed in the interim. This study has identified a diversity of past drought from short extreme drought to long protracted drought events. However, the long drought event of 1854-1860 which lasted for more than 70 months across much of Ireland would be a good benchmark drought for testing current and future water resilience. Many of the Irish catchments are groundwater dominated and this study has shown that long duration droughts more adversely affect the flow at many of these catchments. Moreover, past events challenge water managers to consider how they might manage any of these past drought episodes, given the present supply-demand balance, and condition of infrastructure (much of which is the same as in the 19th Century).

6.4 Limitations and Priorities for Future work

There is much scope for developing the initial work in chapter 3. One of the limitations of this research was the quantity of available IIP stations. Recently, Met Éireann has sorted, organised and catalogued most of the hard copy archived Irish precipitation records. This paves the way for future work to add stations to the IIP network by rescuing additional hard copy records using the methods presented in chapter 3. A larger IIP network would be particularly important for increasing confidence in the homogeneity of early parts of the record. Increased station density would also add confidence in break detection for stations with low correlations among reference networks. In addition, increasing the station network would address the spatial bias issue within the current IIP network which is caused by the lack of station coverage in certain regions. Furthermore, there are some daily weather observations available in the hard copy records in the Met Éireann archives. There is a priority for these daily records to be rescued, digitised and if possible quality assured. The long-term daily records would allow for past extreme events such as flooding and extreme hot/cold days to be identified and assessed. Similar to this study documentary evidence could be used to validate and add confidence to the results.

Uncertainty estimation in data homogenisation was out of the scope of chapter 3 and this is one of the limitations of this study. Future work needs to be prioritised to determine uncertainty estimates for data homogenisation using HOMER. It is important that the limitations of homogenised data are assessed and made available to all future users.

Undetected inhomogeneities may introduce both temporally and/or spatially correlated errors. Systematic errors at stations (due to continuous measurement bias) can also introduce errors. The potential errors are complex but future work could use real data and metadata for validation and provide some estimation of expected errors for ongoing studies. In addition, an estimate of ordinal error for every station would be helpful to check if the analysis is dependent on the quality of homogenisation.

Another limitation of this study was the lack of long-term temperature records for Ireland. There are some temperature records at Markree, Birr and Dublin available but these have not yet been homogenised or quality assured. There are further long-term hard copy temperature records held in Met Éireann archives. Researchers in the Irish Climate and Research Units (ICARUS) Maynooth are collaborating with Met Éireann to digitise these records and eventually conduct homogenisation methods for data quality assurance. Given that evaporative losses can exacerbate summer drought it would be important that future work uses a drought indicator that incorporates this variable (e.g. Standardized Precipitation-Evaporation Index; Vicente-Serrano *et al.,* 2010). The quality assured long-term temperature records could be used to calculate potential evapotranspiration (PET) using temperature based methods. The derived PET could be assessed for monthly bias and calibrated using a current observed baseline of PET records (e.g. Lennard *et al.,* 2015) and incorporated into future Irish drought analysis.

Exploring potential climatological drivers of variability and change in precipitation and drought rich periods was out of the scope of this study, primarily due to time constraints. Ireland's sentinel location along the Atlantic fringe provides a great opportunity for future work to assess the main large scale drivers of changes in long-term hydro-climatology in this region. Such knowledge is essential for establishing how climate variability and change might influence future changes in precipitation and drought occurrence.

This work provides a first pass reconstruction of long term river flows and as such there is much scope for improving this analysis. Catchment rainfall runoff (CCR) models are a simplified representation of a real-world system and the selection of model structure is usually a subjective decision made by the modeller (Wagener, 2003; Wilby, 2005). As stated in Chapter 5 the model parameters cannot be measured and need to be estimated, they are also assumed to be constant over time. It is widely acknowledged that most uncertainty in CRR models comes from model structures and parameter selection (e.g. Wagener *et al.*, 2003; Wilby, 2005; Murphy *et al.*, 2006). *Equifinality* exists where many model parameter combinations can generate a satisfactory simulation (Wilby, 2005). To address the parameter uncertainty issues future work could use the Generalized Likelihood Uncertainty Estimation (GLUE) procedure (Bevin and Freer, 2001). The GLUE method uses Monte Carlo Random Sampling (MCRS). Each parameter set is classified as behavioural or non-behavioural by assessing whether it performs above or below a pre-defined threshold (Murphy *et al.*, 2006). This method allows for parameter uncertainty to be quantified. In addition, only one CRR model was employed in chapter 6, future work could use other CRR models to explore additional model structures in reconstructing Irish river flow. Increasing the number of long term rainfall stations available as part of the IIP would also increase confidence in reconstructed flows. At times this study was forced to use rainfall stations outside of catchment boundaries with subsequent deterioration in model performance. A larger number of rainfall stations would also facilitate an increased sample of catchments for reconstruction so that a more in depth understanding of the role of catchment characteristics in drought propagation could be explored. Furthermore, influence of snow during colder periods can cause modelling output errors (Jones *et al.*, 2006). In addressing this issue future work could incorporate long term temperature records into the CRR models to simulate snow and snow melt.

It is important to understand the links between meteorological drought and hydrological drought. Particularly crucial for water resource management is the amount of time it takes precipitation deficits to circulate through the hydrological cycle into river flow deficits. The results presented in chapter 5 show good potential for the SPI to be used as a hydrological drought forecasting tool. The correlation results of the SPI and Q95 flow are only initial results and caution must be taken, but are encouraging and warrant future research. This study limited the assessment to four catchments; hence future work should expand the lagged correlation analysis to include more study catchments with more varied catchment sizes and characteristics.

Recent work by Barker *et al.* (2016) also investigated the relationship between SPI values at different time scales and Standardized Streamflow Index (SSI). The study investigated different probability distributions and found the *Tweedie* distribution was an acceptable fit for both precipitation and river flow in the UK (Barker *et al.*, 2015). Future work could explore if the *Tweedie* distribution can be used for Irish river flow and if so the relationship between SPI and SSI could be further assessed. Finally, this work would also allow for hydrological drought to be compared across varying catchment types located in different regions.

6.5 Chapter conclusion

This chapter has provided a synthesis of the key thesis themes while emphasising the value of long-term records, metadata, and documentary evidence. This chapter has also discussed the research limitations and identify priorities for future research. The next chapter will present the thesis aims and each objective along with a summary of key findings and will show the final closing comments.

7 Conclusion

7.1 Introduction

Although each chapter presents individual focused discussions and conclusions, this final chapter aims to provide a summary of the key research findings from the body of work undertaken. This chapter will also present the final closing comments.

The overarching aim of this thesis was to rescue and transcribe hard copy long-term monthly precipitation records for the island of Ireland and to supplement the existing series. To quality check, analyse and assess the records for variability and change and identify past drought events. To integrate past documentary evidence adding confidence to the data and present some of the social economic impacts from past drought events. To reconstruct long-term river flow records utilising the good quality monthly precipitation records and asses the flow for past drought events.

The aims were addressed by the following five objectives set out in Chapter 1:

Thesis objective 1: Expand and extend the existing long-term monthly precipitation catalogue for Ireland by digitising hard copy archived monthly precipitation and compile detailed metadata and station history from all available sources **(Chapter 3)**

Thesis objective 2: Check the precipitation records for homogeneity using state of the art methods **(Chapter 3)**

Thesis objective 3: Examine how precipitation has changed in Ireland at the longer time scale **(Chapter 3)**

Thesis Objective 4: Produce a detailed historical drought catalogue for Ireland and integrate qualitative historical documentary evidence to validate and add further confidence to the quantitative assessment **(Chapter 4).**

Thesis objective 5: Use the precipitation records from objective 2 to reconstruct long-term monthly river flow records at selected Irish catchments and identify historical hydrological droughts **(Chapter 5).**

7.2 Summary of key research findings

7.2.1 Thesis Objective 1: Expand and extend the existing long-term monthly precipitation catalogue for Ireland by digitising hard copy archived monthly precipitation and compile detailed metadata and station history from all available sources (Chapter 3)

The literature review presented in Chapter 2 clearly identified that Ireland lacks long-term quality assured precipitation records. Chapter 3 expanded the existing catalogue of long-term monthly precipitation stations by digitising available hard copy records held in Met Éireann's archives for an additional eight stations. Where valuable but discontinuous records were available this study reconstructed composite series by utilising bridging and infilling techniques. This chapter compiled a long term monthly precipitation series at 25 stations across the island of Ireland (Island of Ireland Precipitation (IIP) network) with varying start and end dates. This chapter also compiled all available metadata and station notes for the 25 stations to assist in the homogenisation process.

7.2.2 Thesis Objective 2 Check the precipitation records for homogeneity using state of the art methods (Chapter 3)

To homogenise the expanded catalogue of 25 IIP stations Chapter 3 employed the HOMER (HOMogenisation softwarE in R) package which represents a synthesis of homogenisation approaches of the HOME COST action. HOMER detected and corrected inhomogeneities in the 25 stations and extended all records to a common period 1850-2010.

The homogeneity test on the newly created Island of Ireland precipitation (IIP) network identified 53 data outliers across all stations, with 25 breaks detected across 14 of the IIP stations. Seven IIP stations were affected by multiple breaks and seven stations had only one break. The detected breaks were evaluated by scrutiny of compiled metadata. Results show that 20 of the breaks could be attributed to issues such as changes in gauge size and position, station closures and moves, previous infilling/bridging and updating of records. Correspondence between detected breaks and available metadata demonstrated the value of combining both qualitative and quantitative techniques in data homogenisation. The five unexplained detected breaks were assessed and verified as legitimate by employing the Mann Kendall test. Given the suspicion raised by the MK test results around the years of the detected issues all the detected breaks were adjusted. Therefore, this work has produced (for the first time) a homogenous quality assured long-term monthly precipitation network for Ireland (***Thesis Objective 2).*** This work also represents the first published application of HOMER to precipitation data with methods showing promising for use in other regions. The dataset and metadata produced for each station, together with a composite Island of Ireland series (mean across all 25 stations) are freely available for use and download at: http://hdl.handle.net/2262/76134 with the hope that they can inform future research and be integrated into teaching.

7.2.3 Thesis objective 3: Examine how precipitation has changed in Ireland at the longer time scale (Chapter 3)

There have only been a few studies into changes in long-term precipitation for Ireland and all have been limited to a small number of stations for which data quality was uncertain. Chapter 3 also addresses this important knowledge gap. While chapter 3 flags caution at some stations, there is increased confidence in trends identified from the IIP series due to detailed metadata for each station and the coherence of trends across the network. In addition, the IIP series show good consistency with the England and Wales Precipitation Series (Alexander and Jones, 2001) and the British-Irish Isles cyclone metrics (Matthews *et al.*, 2016). The study identified notable monthly extremes over the past 150 years. The years 1891 and 1964 stand out as the driest winters at nine and six of the IIP stations respectively. The wettest ranked winters across 12 stations occurred in 1877, 1994 and 1995. The summer of 1995 was the driest at 6 stations (east and southeast) while 1976 was driest at 3 stations (midlands and northeast) since 1850. 1861 ranks as the wettest summer for 8 stations located along the west coast while 1958 is wettest for stations in the east. The 2000s also stand out because of wet summers (in 2007, 2008 and 2009). Spring 1947 was the wettest for 15 stations with both 1995 and 1976 notable as the driest springs **(Thesis Objective 3).**

The assessment of trends in for all combinations of start and end years using the Mann Kendall test indicate positive trends in winter precipitation and negative trends in summer over the period 1850-2010. The trend results following data homogenisation showed changes in magnitude and direction in trends at some stations. Malin Head has been analysed in previous studies (e.g. McElwain and Sweeney, 2007) and significant annual increasing trends were detected 1890-2003. However, post homogenisation no annual trends were present at Malin Head with similar results found for winter. In addition, summer trends pre-homogenisation at Malin Head indicates no trend while post homogenisation trends show significant decreasing trends. These results show the importance of assuring that climate records are homogenous as misleading trends can be present. More importantly, the trends in shorter records commencing post 1940 are not representative of the detected trends since 1850. The long-term homogenous records show that in most cases trends over the period 1940-2010 contradict the trends detected over the period 1850-2015. These results show the importance of long-term records as short records can also produce misleading trends **(Thesis Objective 3).**

7.2.4 Thesis Objective 4: Produce a detailed historical drought catalogue for Ireland and integrate qualitative historical documentary evidence to validate and add further confidence to the quantitative assessment (Chapter 4).

The literature review highlighted that there has been a paucity of historical drought research in Ireland. Chapter 4 addresses this important knowledge gap by producing a 250-year drought catalogue for the island of Ireland. Firstly, this chapter updated the IIP network 1850-2010 to December 2015. Where station closures have occurred or no data were available, bridging using correlated neighbouring station records was undertaken using linear regression to derive seasonal adjustments (as in Chapter 3).

Historical droughts in the updated IIP network and Island of Ireland (IoI) composite (arithmetic mean of all stations) over the period 1850-2015 were identified using the widely used Standardised Precipitation Index (SPI) (e.g. McKee *et al*., 1993; Guttman, 1999; Lloyd-Hughes and Saunders 2002; Redmond, 2002; Van Loon, 2015). Chapter 4 also developed an extended (250 year) year drought catalogue for Ireland by using gridded precipitation reconstructions that were extracted for the Irish land area to produce a composite series of monthly rainfall totals for the period 1765-1849. This process would not have been possible without execution of **objective 2.** The extended monthly series (December 1765 to December 1849), referred to as IoIext, was analysed separately to the IIP observations. Documentary sources were used to confirm the occurrence of identified drought events and to examine and present their socio-economic impacts.

Results in chapter 4 highlight the unusualness of the recent record and how unrepresentative the period since 1980 is of the long-term drought climatology of the island. The large decline in drought events around the 1990s is consistent in timing with the regime shift in Atlantic Ocean influence on European climate identified by Sutton and Dong (2012).

The results show that, contrary to recent experience and public perception, the island of Ireland is surprisingly drought prone. The IoI (1850-2015) and IoIext (1765-1849) series revealed 68 individual drought events over the last 250 years. Chapter 4 identified seven major drought rich periods in the IIP network during 1850-2015 with drought events lasting (>18 months) impacting simultaneously at least 40% of the study sites in 1854-1860, 1884-1896, 1904-1912, 1921-1924, 1932-1935, 1952-1954 and 1969-1977. The detailed analysis of the SPI shows the substantial diversity of drought events in terms of development, severity and spatial extent **(Thesis Objective 4).**

Results for the IoIext series (1765-1849) identified a further seven long duration droughts (>18 months) during 1784-1786, 1800-1804, 1805-1806, 1807-1809 1813-1815, 1826-1827 and 1838-1939. Many of these drought events occurred during or immediately prior to Irish famine events, most notably the *Great Irish Famine* 1845-1849 (Ó Gráda, 2015). Additionally, the drought periods identified over the past 250 years in Ireland show good coherence with drought periods identified in the UK (e.g. Marsh and Cole, 2006; March *et al.*, 2007; Todd *et al.*, 2013) **(Thesis Objective 4).**

The results of this chapter highlighted two particularly long duration drought events based on the studies drought criteria. The 1854-1860 drought event lasted 73 months and apart from only a few months reprieve the 1800-1804 event would have persisted for 100 months. Documentary evidence has provided important insights into the impacts from past severe drought in Ireland, particularly for those early in the record and throughout the reconstruction period. Impacts include reduced or failed crop yields, increased crop and dairy prices, human and livestock health issues, water restrictions, low reservoir levels, water supply failures and hydro-power reductions. Extensive integration of documentary sources from newspaper archives also increases confidence in the droughts identified across the 250 years of record. The work shows the importance of combining qualitative and quantitative evidence of historical droughts, which provides crucial information allowing for a much clearer understanding of drought development and impacts (**Thesis Objective 4).**

Chapter 4 makes available vital information on a diverse set of drought conditions over the last 250 years. The information can be used to stress-test current and planned infrastructure, first and foremost in the water sector (e.g. Spraggs *et al*., 2015; Watts *et al.*, 2012). For this reason, Appendix 2 provides the detailed information on all droughts (duration, mean intensity, accumulated deficits and maximum intensity) identified for each of the 25 IIP network stations (1850-2015) **(Thesis Objective 4).**

7.2.5 Thesis objective 5: Use the precipitation records from objective 2 to reconstruct long-term monthly river flow records at selected Irish catchments and identify historical hydrological drought (Chapter 5).

River flow records in Ireland are relatively short with most records only starting in the 1970's. Chapter 5 used the homogenous long-term monthly precipitation records and long-term average PET data to the run the conceptual rainfall runoff model HYSIM. The chapter reconstructed long-term river flows at 12 study catchments (1850-2015). Chapter 5 builds on Chapter 4 and provides important information on past hydrological drought in Ireland.

Chapter 5 used two indices to identify drought in the reconstructed river flows; the Drought Severity Index (DSI) to identify general drought events and the Q95 flow to identify severe drought events. Noteworthy years with the longest duration droughts are as follows: 1855-1860, 1887-1888, 1891-1894, 1902-1912, 1933-1934, 1953, 1971-1976. The hydrological droughts identified in Chapter 5 are much shorter than the meteorological droughts identified in chapter 4. The differences in drought duration could be due to intermittent periods of precipitation, or that many study catchments are groundwater dominant and are recharged from storage. The longest DSI droughts show a range of durations from 8 months (1850) to 22 months (1854-1855). The drought periods identified in chapter 5 show good consistencies with previous UK studies (e.g. Jones *et al.*, 2006; Marsh *et al.*, 2006; Todd *et al.*, 2013; Spraggs *et al.*, 2015) and highlights the large spatial extent of historical droughts. The information presented in Chapter 5 is crucial for appropriate Irish water systems management.

A key result from Chapter 5 showed that different SPI accumulation time scales correlate with each Q95 monthly flow. The results indicate that shorter SPI accumulations (SPI-1, SPI-2) correlate strongly with monthly Q95 flow at catchments with a low BFI. However, longer SPI accumulations (SPI-3 to SPI-6) correlate strongly with monthly Q95 flows at catchments with high BFI. These are important findings and could be used as a guide for producing drought estimation for ungauged catchments with similar characteristics. Additionally, 1-month lagged SPI accumulations (SPI-1 to SPI-3) significantly correlate (0.05 level) with monthly Q95 flow at catchments with high BFI. In addition, the 2-month lagged SPI-1 and SPI-2 show a correlation with monthly Q95 flow at Boyne 7012 (high BFI). Although the study sample size is limited to four catchments the initial results indicate that SPI has potential to be used as a hydrological drought forecasting tool.

7.3 Final remarks

This thesis produced (for the first time) a homogenised precipitation network of 25 stations for the island of Ireland. The precipitation network analysis has contributed considerably to knowledge by providing important insights into variability and change over the longer term. In addition, this thesis has produced (for the first time) a detailed 250-year drought catalogue for the island of Ireland. This work contributes significant new knowledge that can be used for stress-testing the resilience of planned Irish water resource developments. By combining qualitative and quantitative evidence of historical droughts this thesis has provided a more coherent understanding of drought development and historic impacts. Using the long-term precipitation record this study reconstructed river flow (for the first time) at 12 Irish study catchments 1850-2015. Hydrological drought was identified in the reconstructed river flow highlighting the diversity of historical drought in Ireland. Finally, this thesis has fully utilised the long-term precipitation records to present (for the first time) a 250-year hydro-climatology of the island of Ireland.

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Appendix 1 IIP station metadata information

Page	*Station*	*Metadata sources*
184	Ardara Killarney Cappoquinn	Briffa, (1984) Personal communications with Prof Phil Jones Climate Research Units UK
185	Belfast Derry	Personal communications with Prof Phil Jones Climate Research Units UK Met Éireann Tabony, (1980)
186	Phoenix Park Birr	Personal communications with Prof Phil Jones Climate Research Units UK Tabony, (1980)
187	Valentia Cork Airport	Personal communications with Prof Phil Jones Climate Research Units UK Met Éireann Tabony, (1980)
188	Waterford	Met Éireann Tabony, (1980)
189, 190	Markree	Personal communications with Prof Phil Jones. Climate Research Units UK. Met Éireann Tabony, (1980).
191	Armagh Malin Head	Personal communications with Prof Phil Jones Climate Research Units UK. Met Éireann Tabony, (1980). Armagh Observatory
192	Roches Point Dublin Airport	Personal communications with Prof Phil Jones. Climate Research Units UK Met Éireann Tabony, (1980)
193	Mullingar	Met Éireann
194	Rathdrum Athboy	Met Éireann
195	Strokestown Foulkesmills	Met Éireann
196,197,198	Portlaw	Met Éireann
199	University College Galway	Met Éireann
200,201	Drumnsa Shannon	Met Éireann Tabony, (1980)
202	Enniscorthy	Personal communications with Prof Phil Jones Climate Research Units UK Met Éireann Briffa, (1984)

Note: All metadata contained in these tables has been directly transcribed from original source.

Station name and County	Composite Stations, Period ,Correction factors (CF) ,Gauge information where available: Gauge Diameter-Rim height above ground ,altitude above sea level in feet	Station Notes
Ardara, Donegal	Londonderry (Tabony) 1870-1994 CF 1.57 - Inver Globe 1875-1882 CF 1.34 - Londonderry (Tabony) 1883-1886 CF 1.57 - Killybegs 1887-1909 CF 1 - Killybegs Rockmount 1910-1931 CF 0.987 - Londonderry (Tabony) 1932-1934 CF 1.57 - Dunkineely 1935-1940 CF 1.42 - Londonderry (Tabony) 1941-1950 CF 1.57 - Ardara, Wooodhill 1951-1980 CF 1 - Bridged to 2010 using Glenties Hatchery 1923-2013 Winter CF 0.94, Spring CF 0.93, Summer CF 0.91, Autumn CF 0.94.	Constructed by Briffa (1984) using the 10 year sheets of the rainfall Archives of the UK Met Office before 1940 and post 1940 from the Irish Met service. Also records from Tabony were used for certain periods. Update in Jones and Conway 1997 up to 1994 using data from Met Eireann. Ardara was updated from Glenties Hatchery stno 441 from 1994-2010 for this research.
Killarney, Kerry	Valentia 1861-1881 CF 0.91 - Killarney, Kerry 1882-1899 CF 0.93 - Killarney Asylum 1900-1971 CF 1 - Valentia 1972-1976 CF 0.91 - Killarney Asylum 1976-1980 CF 1 - Killarney stno 3205 1968-2013 Winter CF 1.19, Spring CF 0.93, Summer CF 1.10, Autumn CF 1.13.	Constructed by Briffa (1984) using the 10 year sheets of the rainfall Archives of the UK Met Office before 1940 and post 1940 from the Irish Met service. Also records from Tabony were used for certain periods. Update in Jones and Conway 1997 up to 1994 using data from Met Eireann. Killarney was updated from Killarney stno 3205 from 1994-2010 for this research.
Cappoquinn, Waterford	Cappoquinn 1870-1877 CF 1.39 - Clonmel, Glenam 1878-1878 CF 1.45 - Cappoquinn 1879-1879 CF 1.39 - Clonmel , Glenam 1880-1884 CF 1.45 - Cappoquinn, Mt Melleray 1885-1907 CF 1.25 - Lismore Castle 1908-1908 CF 1.45 - Cappoquinn, Mt Melleray 1922-1925 CF 1.15 - Cork (Tabony) 1926-1926 CF 1.31 - Knockaderry Res no 1 1927-1930 CF 1.37 - Knockaderry Res no 2 1931-1933 CF 1.32 - Lismore Castle 1934-1940 CF 1.31 - Knockaderry Res no 1 1941-1943 CF 1.28 - Cappoquinn, Mt Melleray 1944-1973 CF 1 - Knockaderry Res no 1 1974-1978 CF 1.28 - Cappoquinn, Mt Melleray 1944-1980 Winter CF 1, Spring CF 0.99, Summer CF 0.99, Autumn CF 0.98.	Constructed by Briffa (1984) using the 10 year sheets of the rainfall Archives of the UK Met Office before 1940 and post 1940 from the Irish Met service. Also records from Tabony were used for certain periods. Update in Jones and Conway 1997 up to 1994 using data from Met Eireann. Cappoquinn was updated from Cappoquinn (Mount Mellery) stno 1106 from 1994-2010 for this research.

Station name and County	Composite Stations, Period ,Correction factors (CF) ,Gauge information where available: Gauge Diameter-Rim height above ground ,altitude above sea level in feet	Notes
Belfast, Antrim	Linen Hall 1812-1831 CF 1.2 11 inch gauge 4ft above ground ALT 12 - Corsewell Pt 1832-1835 CF 1.17 11 inch gauge 4ft above ground ALT 12 - Linen Hall 1836-1859 CF 1.2 5 inch gauge 4 ft 9 inch above ground ALT 17 - Queens College 1860-1904 CF 1.2 5 inch gauge 4 ft 9 inch above ground ALT 17 - Queens College 1905-1955 CF 1.17 - Lagmore Reservoir 1956-1977 5 inch gauge 1 ft above ground ALT 58. Updated using Hillsborough Winter CF 0.83, Spring CF 0.85, Summer CF 0.81, and Autumn CF 0.85.	Constructed by Tabony 1980. 1832-1835 incomplete, 1871-1874 missing, moved to Royal Academic Institute. 1902 estimates, Inspections in 1919 & 1927 good. 1958 inspection; over exposed NE & SE non- standard turf wall. Records bridged from 1977 to 2010 using records at Hillsborough station for this research. The ratio of 1.173 between Lagmore and Queens College is obtained from an overlap 1939-1955. The raising of the ratio to 1.208 before 1905 when Queens College gauge was elevated is obtained from overlap between Queens College and Springfield 1899-1910. The ratio between Linen Hall and Queens College was 1.06 over the period 1860-1903, but 0.91 in period 1852-1859. The homogenised record has been created by assuming a ratio of 1, then higher altitude of Queens College cancelling the effect of the raised suite of the gauge. The Belfast record before 1860 must therefore be open to considerable doubt. The missing data from the Linen Hall from 1832-1835 was obtained from Corsewell Point based on the overlap with the complete Belfast record from 1840-1960.
Derry, Derry	Londonderry Literary Association 1861-1864 CF 1.08 12 inch gauge 40 ft above ground ALT 50 - Londonderry, Moneydigs 1865-1910 CF 1.05 5 inch gauge 1 ft above ground ALT 80 - Limavady, Drenagh 1861-1933 5 inch gauge, 1 ft 6 inch above ground ALT 60 - Londonderry, Moneydigs 1934 onward CF 1.05 5 inch gauge 1 ft above ground ALT 121. Updated to 2010 using Coleriane, Winter CF 0.98, Spring CF 0.99, Summer CF 0.96, and Autumn CF 1.28.	Constructed by Tabony 1980. Howard gauge in middle of lawn,1916-50 rejected, 1956 NP high, 1958 inspection of gauge poor but very good site, 1898 gauge moved 42 yards south, 1925-37 missing, New gauge in almost same place as original .1965 inspection no better site. Records bridged from 1976 to 2010 using records at Coleraine station for this research.

Station name and County	Composite Stations, Period ,Correction factors (CF) ,Gauge information where available: Gauge Diameter-Rim height above ground ,altitude above sea level in feet	Notes
Phoenix Park Dublin	Phoenix Park 1837-1852 CF 1.04 gauge 8ft above ground ALT 167 - Phoenix Park 1853-1854 CF 1.05 gauge 10ft above ground ALT 159 - Phoenix Park 1855-1860 CF 1.035 gauge 3ft and 10ft above ground ALT 159 - Phoenix Park 1861-1862 CF 1.035 gauge 6 ft 6 inch above ground ALT 166 - Phoenix Park 1863 CF 1.05 gauge 10 ft above ground ALT 159 - Phoenix Park 1864 CF 1.04 gauge 7 ft above ground ALT 166 - Phoenix Park 1865-1869 CF 1.04 gauge 10 ft above ground ALT 169 - Phoenix Park 1870-1872 CF 1.05 gauge 10 ft above ground ALT 170 - Phoenix Park 1873 CF 1.05 gauge 10ft above ground ALT 159 - Phoenix Park 1874-1875 CF 1.05 gauge 10ft above ground ALT 170 - Phoenix Park 1876-1877 CF 1.01 gauge 2ft 7 inch above ground ALT 170 - Phoenix Park 1878-1879 CF 1.015 gauge 3ft above ground ALT 163 - Phoenix Park 1880-1892 CF 1 gauge 1ft above ground ALT 164 - Phoenix Park 1893 onward CF 1 1ft above ground ALT 155.	Constructed by Tabony 1980. Some of these changes in altitude may be due to re-surveys.the multiplying factors used are related to the height of the rim of the gauge above ground and are determined from overlaps with gauges at Trinity College and Monkstown. Inspection 1906 very clear open site. 1913 the observatory is in an open filed surrounded by plantation of firs. No conspicuous object within distance. Gauge moved 2.4m NW 1920.1924 Inspection satisfactory.1936 gauge moved 91m East. Records appended and updated from 1994 to 2010 from Phoenix Park station records for this research.
Birr, Offaly	Port Arlington 1845-1861 CF 1.095 15 inch square gauge 12 ft above ground ALT 236 - Birr Castle 1862-1872 8 inch gauge 8 inch above ground ALT 200 - Birr Castle 1873-1879 8 inch gauge 8 inch above ground ALT 183 - Birr Castle 1880-1883 8 inch gauge 8 inch above ground, ALT 180 - Birr Castle 1884-1886 8 inch gauge 11 inch above ground ALT 170 - Birr Castle 1887-1889 8 inch gauge 8 inch above groundALT 180 - Birr Castle 1890-1909 8 inch gauge 11 inch above ground ALT 180 - Birr Castle 1910-1914 8 inch gauge 1ft above ground ALT 183 - Birr Castle 1915-1932 8 inch gauge 1ft above ground ALT 175 - Birr Castle 1933-1940 8 inch gauge 1ft above ground ALT 173 - Birr SWS 1941- onward 8 inch gauge 1ft above ground ALT 173- Bridged and updated from 2000 to 2010 using records at current Birr station, Winter CF 0.99 , Spring CF 1.00, Summer CF .99, Autumn CF 0.99.	Constructed by Tabony 1980. The ratio of 1.095 comes from an overlap 1866-1885. From 1862 to 1865, Port Arlington was too high. Gauge change around 1860 from 15 inch square to 8 inch round. Comparison with neighbouring stations suggests no corrections for changes of gauge before 1865.1872 estimated. 1941 onwards regarded as continuation of Birr Castle. Records updated from 2000 to 2010 from records at Birr station for this research.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Valentia, Kerry	Knightstown, Valentia Island 1861-1865 CF 1.025 8 inch gauge 2ft 6 inch above ground 38 - Valentia Observatory, Valentia Island 1866 - 1875 CF 1.025 8 inch gauge 3 ft above ground ALT 11 - 1876-1879 CF 1.025 8 inch gauge & 2 ft above ground 12 - 1880-1892 CF 1.025 11 inch gauge 2 ft above ground ALT11 - Valentia Observatory, Mainland 1893 CF 1.01 8 inch gauge 2 ft above ground ALT 40 - 1894 -1908 8 inch gauge 2 ft above ground ALT 32 - 1909 8 inch gauge 2 ft above ground ALT 62 - 1910-1913 8 inch gauge 2 ft above ground ALT 45 - 1914-1920 11 inch gauge 2ft 8 inch above ground ALT 30 - 1921-1932 8 inch gauge 1ft above ground ALT 30 - 1933-1940 8 inch gauge 1ft 3 inch above ground ALT 30.	Constructed by Tabony 1980 Met Service Monthly weather report station moved from Valentia Island to mainland in 1892.Values from 1921 onwards are as published for Valentia. From 1893-1920 values have been increased by 1% to account for the elevated height of the rim of the gauge above ground. For the change to mainland station, values have been adjusted to take account of a change in average rainfall of 1380mm on the island to 1400mm on mainland site. Knightstown records from 1861-1865 has been regarded as homogenous Appended to 2010 for this research using current station records at Valentia no correction factor needed.
Cork Airport, Cork	Royal Institute (RI) 1836-1845 CF 1.28 - Royal Institution 1846-1851 CF 0.86 - Royal Institution 1852-1884 CF 1.28 - Royal Institution 1836-1884 10 inch gauge 50ft above ground ALT 68 - University College (UCC)1885-1975 - University College 1862-1869 8 inch gauge 5ft above ground ALT 59 1870-1875 8 inch gauge 1ft above ground ALT 65 1876-1975 8 inch gauge 1ft above ground ALT 65.	Constructed by Tabony 1980. New funnel 1877 inspection satisfactory 1931-1940. The UCC gauge in middle of plot of grass in Botanic gardens 1909 Dr Mills report gauge in good condition, free exposure, the RI gauge was on apex of a roof. Changes in altitude at the two stations, as given by the 10 year sheets are clearly due to re-surveys. From 1862-1875 when the UCC gauge was 1.68m above ground, the ratio UCC/RI =1.234.No significant seasonal variation in then ratio was found. Comparisons between UCC and Inistogue suggest that lowering the UCC gauge from 1.8m to 0.3m increases the rainfall by 3.7%.This value has low confidence but seems reasonable. Station prior to 1961 was UCC at an altitude of 17 metres after 1961 records were found to be from Cork Airport at an altitude of 155 metres above sea level. Thus the ratio between UCC gauge at 0.3m and the RI =1.234 x1.037=1.28.Comparisons between the RI and Waterford between 1862-1875 give a ratio of 1.25 a level which is generally maintained to the start of the Waterford record in 1841. 1846-1851 marked discontinuity when the ratio drops to 0.844.The RI is recording far too much perhaps due to use of incorrect measure. 1846-1851 the ratio UCC/RI has been taken as 1.28 x 0.844/1.25=0.864.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Waterford, Waterford	Inistogue 1843-1859 CF 0.995 5 inch gauge 4 ft above ground ALT 116 - 1860-1869 CF 0.995 5 inch gauge 4 ft above ground ALT 316 - 1870 - 1899 CF 0.995 5 inch gauge 4 ft above ground ALT 400 - 1905-1924 CF 0.985 5 inch gauge 1 ft above ground ALT 400 - Brook Lodge 1875-1878 5 inch gauge 3 ft 8 inch above ground ALT 175 - 1879-1899 5 inch gauge 1 ft above ground ALT 100 - 1900-1931 CF 0.985 5 inch gauge 1 ft above ground ALT 104 - Gortmore 1906-1909 5 inch gauge 1ft 6 inch above ground ALT 100 - 1910-1912 5 inch gauge 1 ft above ground various - 1913-1917 5 inch gauge 1 ft above ground various - 1918 5 inch gauge 1 ft above ground ALT 120 - 1919 5 inch gauge 1 ft above ground ALT 120 - 1920-1948 CF 0.953 5 inch gauge 1 ft 2 inch above ground ALT 137 - Tycor 1938-1971. Bridged and Updated to 2010 using Waterford, Adamstown Winter CF 1.03, Spring CF 1.09, Summer CF 1.01, and Autumn CF 1.01.	Constructed by Tabony 1980. Constructed by Tabony 1980. In 1909 Dr Mill's report: Gauge on open lawns excellently exposed in garden. Records very carefully kept and diagrams for each year and for years total kept in separate book. Dr Mills gauge in open lawns excellent exposure. In this position a year previously less well exposed. In 1.1 m enclosure Camden glass. A number of altitude changes-gauge moved 2 km south Gauge moved north. 1936 inspection site too sheltered moved to centre of new site. Gortmore/Tycor overlap is for 11 years 1938-1948.The Gortmore/Insitogue overlap is for the period 1906-1924 and Brook Lodge/Inistogue overlap is for 1880-1899 and 1910 to 1919. 15 added to Inistogue before 1899 because of the elevated rain gauge. No adjustments were made as a result of the reported changes of altitude in the early part of the Inistogue record. Bridged up to 2010 using records at Waterford Adamstown stno 7412 for this research.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Markree Castle, Sligo	Constructed by Tabony 1980 using Markree Castle records. Wall gauge 1833-1859 2ft 7 inch square gauge 16ft above ground ALT 145- 1860-1869 2 ft square gauge 16 ft 3 inch above ground ALT 145 - 1870-1873 2ft 7 inch square gauge 16 ft 3 inch above ground ALT 148 - 1875 2ft 3 inch square gauge 16 ft 3 inch above ground ALT 148 - 1876 2ft 3 inch square gauge 16 ft 3 inch above ground ALT 148 - 1880-1882 2ft 7 inch square gauge 16 ft 7 inch above ground ALT 148 - 1883 2ft 7 inch square gauge 16 ft 7 inch above ground 148 - 1884-1886 2ft 7 inch square gauge 16 ft 7 inch above ground ALT 148.Comments: The two gauges overlapped in year 1870-73,1875-76, 1880-82 and 1884-86.The effect of the leak in the wall gauge from 1880-1882 is clearly discernible. The remaining 9 years overlap have steady ratio of 1.119. No seasonal variation in the ratio was found. . No seasonal variation in the ratio was found. Remarks: 1883 wall gauge records missing leak discovered. 1877-1879 estimates form wall gauge, 1884 part estimates from wall gauge. 1884-1886 Wall gauge shows signs of leakage, record ended in 1886 - Lawn Gauge 1870-1873 5 inch gauge 6 inch above ground -1874-1883 5 inch gauge 6 inch above ground -1884-1902 5 inch gauge 1ft above ground -1903-1905 5 inch gauge 1ft above ground -1906-1915 5 inch gauge 1ft above ground -1916-1917 5 inch gauge 1ft above ground -1918-onward 5 inch gauge 1ft above ground - Records bridged from 1994 to 2010 from records at new Markree station Winter CF 1.01, Spring CF 1.01, Summer CF 1.01, Autumn CF 1.02	1824 Station established in 1824 as astronomical and meteorological station. Astronomy ceased during 1914-18 war as German astronomer was interred. (Telescopes erected in Jesuit College Hong Kong) Met observations continued by his assistant until 01/07/19511833 rainfall 1833-1863 original square gauges (1 square yard) on top of library 16' above ground. 1875-1881 comparison 5" gauge, 6 inches above ground gave a correction figure of-multiply by 1.2045 (Total rainfall 1833-1863= 37.254in (original) becomes 44.87 in corrected). Further detailed info re temp and sunshine averages for these years in file. A history of station from "Symons's Magazine" 1902 in this file.28/03/1939 observations observer to continue after threat of closure. 3 observations per day from now on.26/05/1951 observations observer to retire. (50 years). Will wait until new observer is appointed. 03/07/1951 observations new observer instructed on 3rd and 4th July25/10/1951 inspection satisfactory06/07/1953 inspection screen and gauge need replacing. Bigger enclosure needed. Observer to continue.12/10/1953 enclosure new enclosure laid out.16/10/1953 enclosure fencing complete. New gauge, G-min, screen and thermometers installed.17/10/1953 observations begin at new enclosure.

Station name and County	Notes, Continued	Notes, Continued
Markree Castle, Sligo	Comparison readings from old enclosure to be taken.25/01/1954 observations comparison readings too variable.02/12/1954 observations comparison readings cease.01/07/1957 rainfall amounts are lower than neighbouring sites rainfall since 1947.17/07/1957 inspection all in order including rain-gauge. No evidence of shading. Higher rainfall in other stations may be due Ox mountains and Lough Gill27/02/1958 inspection all in order. Rain-gauge has not been moved more than a few feet since 1916. Old gauge examined but no fault found. Youngest trees in area over 30 years old.09/12/1959 inspection usual high standard28/06/1960 inspection all in order.21/11/1966 observations observer died.19/01/1967 inspection new observer extra instruction given. Dependable.06/01/1970 Some readings missed (A Week?)04/03/1981 Station old astronomers derelict cottage being renovated and will leave enclosure almost at the front door. (No objection at moment) 04/04/1984 inspection exposure very good.	Excellent station.01/04/1985 observations 10 days missing in April 1985 due observers fear of bull near enclosure.01/04/1985 observations 10 days missing in April 1985 due observers fear of bull near enclosure.12/04/1985 observations note stating regret at break in continuity and looking forward to receiving observations from new site at Colooney.18/04/1985 Station new climate station established at Colooney 2 miles away. Observer from Markree moved here. Screen gauge and rain-recorder. OBEs commence 19/04/1985.22/04/1985 observations new observer in Markree. One daily observation of rainfall and temperature.1874-1876 Casella 2147 (110 ft above sea level, 4" above ground) added in Dec 31 to Jan 1st rainfall (.178) ,Records entered to preceding day, recorded by Master of the Workmen (Jan20th -Jan 27th) and thereafter by Anna Doberck, on gauge Casella 2147 (110 ft above sea level, 5.5" above ground) 1877-1882 Records entered to preceding day, recorded by E Sallis on (148 ft above sea level, 16ft above ground)upper gauge1883-1897 Records entered to preceding day, recorded by A Marsh on (148 ft above sea level, 16ft above ground)upper gauge1888-1892 Records entered to preceding day, recorded by E Reynolds and F W Henkel on (148 ft above sea level, 16ft above ground)upper gauge and additional entries from lower 5" gauge level gauge (1 ft off ground 130 ft abs) from Jan-Dec1888-1892 Records entered to preceding day, recorded by E Reynolds and F W Henkel on (148 ft above sea level, 16ft above ground)upper gauge and additional entries from lower 5" gauge level gauge (1 ft off ground 130 ft abs) gauge level gauge (1 ft off ground 130 ft abs) from Jan-Dec 1893-1897 Records entered to preceding day, recorded by A Marsh and E Reynolds on (148 ft above sea level, 16ft above ground)upper gauge and additional entries from lower 5 gauge level gauge (1 ft off ground 130 ft abs) from Jan-Dec1898-1902 Records entered to preceding day, recorded by E Reynolds and F W Henkel on (148 ft above sea level, 16ft above ground)upper gauge and additional entries from lower 5" gauge level gauge (1 ft off ground 130 ft abs) from Jan-Dec1903-1940 Records entered to preceding day, recorded by JR Armstrong on (148 ft above sea level, 16ft above ground)upper gauge and additional entries from lower 5" gauge level gauge (1 ft off ground 130 ft abs) from Jan-Dec gauge shows signs of leakage , record ended,1833-1869 Wall X1.119.1870 onward Lawn.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Armagh observatory, Armagh	Armagh Observatory 1838-2010 ALT 62	Continuous records 1838-2010, see Butler, *et. al* (1998) for details. Updated to 2001 using records provided to this research by Armagh Observatory no correction factor needed.
Malin Head, Donegal	Malin Head S.W.S.(Old Site) Stno145 1890-1975 ALT 72 Malin Head (manual) 1976-2010 ALT 72	From 1890 throughout the period covered, the observations taken at Malin Head consistently recorded the following: barometer and thermometer readings, wind direction and force, extreme wind force, weather, rainfall, sea disturbance and general remarks. Three-times-daily readings were taken at 08:00, 14:00, and 18:00 GMT from 1890 until 1905. We do not have the registers for 1906-1908. From 1909 until 1920, the forms changed slightly to allow readings to be taken at 07:00, 13:00, 18:00 and 21:00 GMT, although measurements were not always taken at each of these times. From 1921 until May 1940, the following fields were added: cloud form and amount, direction and speed of upper cloud, visibility, and a weather diary. 'Temperature and humidity' was added as a field in 1931. Readings during this time were most often taken at 01:00, 07:00, 10:00, 15:00, 18:00 and 21:00, though rarely at all 6 times. From June 1940, readings were also occasionally taken at 04:00 and at 13:00 GMT. In 1946 three-times-daily readings were taken at 07:00, 13:00, and 18:00 GMT, until 1950. From 1951 the times changed to 06:00, midday and 18:00, and on some occasions a fourth reading was taken at 21:00 GMT. From 1954 until April 1955 they were taken at 09:00, midday, 18:00 and at 21:00. In May 1955 a new station opened in Malin Head, and from then on readings were taken on the hour.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Roches Point, Cork	Bridged and updated to 2010 using records at Cork Airport Winter CF 1.14, Spring CF 1.07, Summer CF 0.97, and Autumn CF 1.07.	From July 1873, the registers recorded measurements of the following phenomena: barometer and thermometer readings, wind direction and force, amount of cloud, weather, rain, sea disturbance, and general remarks on the appearance of the weather or on any exceptional phenomena. The daily observations were taken at 8:00, 14:00, and 18:00 GMT, and in August of 1905, duration of bright sunshine was added to the list of fields. In July 1908, the times of readings were changed to 7:00, 13:00, and 18:00 GMT, and from January 1909 until January 1915 they were taken a fourth time daily at 21:00 GMT, with the added field of extreme wind force. In February 1915, ‘direction of upper cloud form and amounts’ was added as a field and remained on the form until 1920. We do not have the monthly registers from 1921-1925, but we do have the summary of observations for readings taken at 7am which gives averages for mean pressure, temperature and humidity, cloud form and amount, visibility, and wind. In 1926, measurements taken at 7:00, 13:00, 18:00, and 21:00 GMT recorded: barometer and thermometer readings, wind direction and force, weather, visibility, cloud form and amount, direction and speed of upper cloud, mean cloud, rainfall, duration of sunshine, and weather diary. From 1948 until 1956, the same readings were taken most commonly at 9:00, 15:00, 18:00, and 21:00 GMT.
Dublin Airport, Dublin	No details available.	No metadata available.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Mullingar, Westmeath	Archived station records transcribed from hard copies at Met Éireann Belvedere Gardens, Mullingar 5 inch gauge 1ft above ground ALT 367 New station 1950 Mullingar Town Stno 2222.	01/01/1943 station opened 01/01/1949 observations new observation hours From 01/01/1949.31/08/1949 surroundings hedge to W interfering with sunshine19/03/1957 rain gauge funnel replaced28/05/1968 surroundings repairs complete07/11/1973 surroundings old station ceases @0900z new station at a new location began @ 1000zNew Station Co-ordinates....Lat 53.32N....Long 07.22W. Old Station Co-ordinates.....Lat 53.31N....Long 07.21W01/03/1991 station ceased to be manned 24 hours06/01/1998 station aws AGI aws came into use 01/07/2002 rain tbrg replaced (0.1mm)09/10/2004 rain tbrg replaced (0.1mm)18/08/2005 rain tbrg replaced (0.1mm)28/06/2006 rain tbrg replaced (0.1mm)28/06/2007 rain tbrg replaced (0.1mm)08/04/2008 station aws AGI aws replaced by TUCSON aws, last observations at 0900UTC#31/07/2008 rain tbrg 0.1 replaced16/02/2009 rain tbrg 0.2 replaced24/07/2009 station aws serviced24/07/2009 rain tbrg 0.1 replaced04/03/2010 rain tbrg 0.2 gauge replaced29/06/2010 station aws serviced29/06/2010 rain tbrg 0.1 replaced30/08/2011 station aws serviced30/08/2011 rain tbrg 0.1 replaced.30/08/2011 rain tbrg 0.2replaced.25/07/2012 station aws serviced25/07/2012 rain tbrg 0.1 replaced./25/072012 Rain tbrg 0.2 replaced. When the original site was selected in Mullingar there were 4 possible sites and from this one was selected. There are photos of the site and plans of the layout too. Nearest objects to gauge -shrubs 8ft-house 28ft-orchard 12ft-garden 3 ft,

Station name and County	*Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet*	*Notes*
Rathdrum, Wicklow	Archived station records transcribed from hard copies at Met Éireann. Avondale House, Wicklow 1908-1956 5 inch gauge 3 inch above ground ALT 420 - Coolatin Shillelagh, Wicklow 1909-1940 5 inch gauge 7 inch above ground ALT 400 Winter CF 0.85, Spring CF 0.877, Summer CF 0.99, Autumn CF 0.95-Fassaroe Bray Wicklow 1872-1915 10 inch square gauge 5ft above ground ALT 250 Winter CF 1.01, Spring CF 0.99, Summer CF 0.98, Autumn CF 0.97 - Updated to 2010 using neighbouring Stations within 30 km - Vartry Lodge stno 624, Roundwood stno 1024, Filter Beds, Roundwood stno 1124, Roundwood, Valve Tower 1940-2012 Winter CF 0.98, Spring CF 0.94, Summer CF 1.00, Autumn CF 0.94.	Missing records 1918-1924 in filled from Coolatin Shillelagh using regression corrections factors as stated.
Athboy, Meath	Archived station records transcribed from hard copies at Met Éireann-Athboy, Frayne 1932-1968 5 inch gauge 9 ft above ground ALT 310 - Athboy, Frankville 1890-1940 8 inch gauge changed to 5 inch gauge in 1936 1ft 3 inch above ground ALT 227 Winter CF 1.18, Spring CF 1.12, Summer CF 1.0O9, Autumn CF 1.17 - Summerhill Gardens, Enfield 1896-1940 5 inch gauge 1 ft above ground ALT 370 Winter CF 0.95,Spring CF 0.97,Summer CF 0.96, Autumn CF 0.95- Updated to 2010 using neighbouring Stations within 30 km: Athboy, Frankville, stno 231 Summerhill, Enfield stno 331, Dunsany Castle stno 431, Kells, Headfort stno 931, Athboy, Frayne stno 1031, Ballivor G.S.stno 1731, Oldcastle, G.E. Schools stno 1931 , Navan, stno 2531 Warrenstown stno 2931, 1941-2010 Winter CF 0.99,Spring CF 0.99,Summer CF 0.97, Autumn CF 1.04.	Frayne, Athboy - nearest objects to gauge - shrubs 8ft-house 28ft-orchard 12ft-garden 3 ft. Frayne, Athboy station missing sporadic monthly data in years 1897 1906 1907 1908 1909 1910 1911 1913 1916 1918 1922 1923 1924. No open station at Athboy since 1993.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Strokestown, Roscommon	Archived station records transcribed from hard copies at Met Éireann Castlenode Strokestown Stno 229 1908-1961 5 inch gauge 2ft above ground ALT 150 –Bridged from 1961 to 2010 using neighbouring donor stations at stno 3729 Scramoge 4229 Strokestown G.S. 4829, Strokestown Elphin st stno1529 Albert lock Winter CF 0.95, Spring CF 0.95, Summer CF 0.93, Autumn CF 0.95.	
Foulkesmills, Wexford	Archived station records transcribed from hard copies at Met Éireann Foulkesmills, Lograigue st no.108, 1874-2012 5 inch gauge 13 inch above ground ALT 210 - Infilled some monthly missing data 1907-1914 from donor station at Ballyhyland,Wexford 1871-1918 5 inch gauge 12 inch above ground ALT 365 Winter CF 1.01,Spring CF 1.01,Summer CF 1.02, Autumn CF 1.04.	Station missing monthly data years in 1907 and 1914 sporadically so in filled from donor station at Ballyhyland Wexford after seasonal regression corrections monthly data used because of issues with missing daily data

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Portlaw, Waterford	Archived station records transcribed from hard copies at Met Éireann Portlaw, Waterford stno 1612 1841-1994 5 inch gauge 48 inch above ground ALT 25 - New station opened 1994-2012 at Portlaw stno 8212 5 inch gauge 12 inch above ground situated 100 metres from old gauge within same grounds.	Date ElementWs309/168: Portlaw Co. Waterford 1612 from 1841 observations, Note on 03/10/1948. Readings date back to 1841. 1861 observations readings being taken by the Malcolmsons since 1861, 13978 inspections Observer had been gardener with original owners and continued to take readings when new owners (Irish Tanneries) took over 5 years ago. 5" gauge with rim 12" above ground in poor state with dent in rim. Good exposure on lawn. 30' high Trees 90' to S. and 25' high house 120' away. 14139 values being entered to day of reading rather the previous day as instructed.14215 rain-measure requested by observer. Present one too small. Request repeated as urgent in Feb and March 103914341 New owners requested to supply new gauge and measure. Refused to supply at first but then agreed15676 rain-measure reported broken16056 observations now done by office staff all queries for 1942 and 1943. The new gauge is M.O. Type in the same position with very good exposure. Rain-measure unsatisfactory and replacement ordered. No readings at weekends or holidays.16778 offices moved to Mayfield House which is nearer to the gauge.17129 gauge in good order. Office closed on Saturdays17746 readings erratic for August 1948. Observer on holidays.19227 mm rain-measure received19309 rainfall for august and September too high. Observer was now measuring with an mm rain-measure and dividing by 2 thinking this would give him the reading in inches.

Station name and County	Notes Continued	Notes Continued
Portlaw, Waterford	19341 10mm rain-measure 5" capacity received 19511 return doubtful. Not accepted. Observer had been absent. 19645 August rainfall satisfactory. July too high.19758 readings now in mm 20010 gauge in good order and records up to date. Plants in border too high and close to gauge. Observers will rectify.21155 rain-measure reported broken. Replacement issued 07/01/195822775 gauge in good order and records up to date. Gauge is now on lawn clear of plants. No weekend readings.23043 rain-measure requested 23686 rim of gauge out of shape and only 7" above ground. To be rectified by observer. (Gauge belongs to Irish Tanneries) records up to date.rim of gauge fractured and repairs unsuccessful. Gauge issued on loan. Records up to date. Rain-measure reported broken. Replacement received 21/08/196723761 rim of gauge fractured and repairs unsuccessful.	Gauge issued on loan. Records up to date. 24701 rain-measures reported broken. Replacement received 21/08/196725204 paid observer to take readings at weekends.25178 10mm rain-measure 5" capacity received25323 drip tube loose. To be repaired locally.25884 drip tube broken off. Screen, gauge, rain-recorder and class A pan at hospital site subject to some interference. Sunshine recorder at safe co.co. Site. 1991 good station/observer. (New observer in training). 1994 excellent station/observer. 1996 thermometers and screen broken. Rain-gauge, rain-recorder, evaporimeter ok. G-min issued. 1997 new site being sought due vandalism. Only sunshine and rainfall reports at moment. 1998 exposure very good. Excellent station/observer. Screen, dry, and wet, max, min, g-min, gauge, rain-recorder, sunshine recorder all in order. 2000 exposure very good.

Station name and County	***Notes Continued***	***Notes Continued***
Portlaw, Waterford	Gauge replaced. Records up to date.26338 new observer will not be able to take weekend readings.26694 gauge in good order and records up to date. 27068 gauge in good order and records up to date. 27689 drip tube loose. Replacement to be issued. Records up to date.28438 gauge in good order and records up to date. New observer. Rain-measure issued.30233 gauge in good order and records up to date. No weekend readings.30707 observer has been made redundant by Irish tanneries but continues to take readings. To be paid from 01/07/198330860 observer could not be contacted 30957 exposure good. Gauge in good order and records up to date. Keen observer.31579 exposure good.	Gauge in good order and records up to date. Keen observer. New site required as he only has access in afternoons.31594 permission sought and granted by phone call to move gauge to observer's large garden.31245 gauge in order and had been read. Observer not present. 31923 gauge in good order and records up to date. Good site in well attended large garden.32395 gauge in good order and records up to date. Good site in well attended large garden.32615 gauge reported broken and replacement requested.34144 Not seen. Observer not present. New gauge and measure needed 34425 station closed 1994. Old station moved to new in 1994-2012 within same grounds 100 yards of old gauge. New file and station number allocated as gauge is too far from original site. (WS309/1535 Portlaw-Mayfield 2) station number 120316/ old number 031215 Air Ministry-Dept of Transport and Power-Meteorological

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
University College Galway, Galway	Archived station records transcribed from hard copies at Met Éireann University College Galway 1861-1965 5 inch gauge 14 inch above ground ALT 64 – New station at University College Galway stno 3927 1965-2011 ALT 45	1965 40' x 40' enclosure surrounded by 8' high wire mesh supported by concrete posts. Established 5" rain-gauge Rain-recorder. Screen, max, min, dry, wet. G-min. 2", 4", 8" soil.max received. 1966 Good observations. Replaced rain-recorder float. Deputy observer for last 2 weeks of July. 1967 Good observations. Anemo has been installed by college. 1969 Good observations. 1970 instruments moved to new site at regional hospital. Wooden "post and rail" fence. 1971 good. G-min and soil temps broken. Not to be replaced due interference. Rain-gauge, recorder and screen ok. 1972 New deputy observer. Good observations. 1976 Good observations. 1977 Good observations. 1979 rain-recorder interfered with. Pen-arm damaged. Replacement requested. 1980 good. No inner can in rain-gauge.1983 very good exposure. Good station. 1984 good station/observer. Sunshine recorder adjusted (to be moved to new site shortly). 1985 good station/observer. 1987 good station/observer. Screen, gauge, rain-recorder and class A pan at hospital site subject to some interference. Sunshine recorder at safe co.co. Site. 1991 good station/observer. (new observer in training). 1994 excellent station/observer. 1996 thermometers and screen broken. Rain-gauge, rain-recorder, evaporimeter ok. G-min issued. 1997 new site being sought due vandalism. Only sunshine and rainfall reports at moment. 1998 exposure very good. excellent station/observer. Screen, dry, and wet, max, min, g-min, gauge, rain-recorder, sunshine recorder all in order. 2000 exposure very good. Due vandalism new secure site proposed. Rain gauge replaced. Thermometers supplied. Dry readings taken from undamaged max. 2004 everything located at good secure fenced site. Rain-recorder need new base plate and float chamber when being installed. 2006 exposure/observer/station good. Rain-recorder to be removed. 2009 excellent station/observer. 2012 Closed. After 46 years (1966-2012) the excellent Mr Gaffney calls it a day.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Drumsna, Leitrim	Archived station records transcribed from hard copies at Met Éireann Albert Lock stno1529 continuous records to date missing monthly values 1921 and 1949 in filled from donor station at Strokestown 5 inch gauge 24 inch above ground ALT 148 Winter CF 1.09, Spring CF 1.08, Summer CF1.05,Autumn,CF 1.12.	1876 gauge appears to have been in existence since 1876. Funnel in a wooden box type. Always considered too low for publication. 1938 record again too low for publication (note from MO). 1939 records of Drumsna have never appeared in British rainfall. 1942 5" gauge 1' above ground leaking. Very exposed open flat country. Partly shaded by fencing. New gauge installed in a sheltered position nearby for comparison. 1943 new gauges are now official instruments here and Drumshambo. Received 5" rain measure. 1944 gauge in good order and records up to date. Protective fencing for rain-gauge completed. 1947 gauge in good order and records up to date. 1954 gauge in good order and records up to date. Protective fencing in poor condition. 1956 gauge in good order and records up to date. 1959 received 5" rain measure. 1959 gauge in good order and records up to date. Bushes to NE need cutting. 1963 gauge in good order and records up to date. Nearby bushes do not affect gauge but may do in future. 1963 received 5" rain measure. 1965 gauge in good order and records up to date. New mm measure issued. 1967 gauge in good order and records up to date. Protective fencing in poor condition. 1967 Protective fencing in very bad condition. 1968 query re low readings. Is gauge blocked or defective? Gauge sited on low ground and may be sheltered. 1969 defective gauge replaced. 1971 up to date. Gauge drip tube missing. Gauge replaced. 1972 up to date. Gauge drip tube loose. Gauge replaced. 1974 gauge in good order and records up to date. Weeds and grass around gauge cut back.

Station name and County	***Notes Continued***	
Drumsna, Leitrim	1976 gauge in good order and records up to date. 1981 gauge in good order and records up to date. Observer retires after 45 years. New observer. Rain-measure replaced. Protective fence needs repair/replaced. 1983 gauge in good order and records up to date. Very good station. 1984 Fair exposure. Very close to bushes. Gauge in good order and records up to date. Rain-measure issued. 1985 Fair exposure. Sheltered by trees and bushes. Gauge in good order and records up to date. 1988 gauge in good order and records up to date. Good site. Well kept. 1993 exposure good. Gauge in good order and records up to date. Rain-measure issued. 1994 Fair exposure. A bit close to hedge. Grass had just been cut and hedge trimmed. Gauge in good order and records up to date. Rain-measure issued. 1997 Fair exposure. A bit close to hedge. Gauge moved 3 yards away. Gauge in good order and records up to date. Rain-measure issued. 1999 exposure good. Gauge in good order and records up to date. 2001 exposure good. Up to date. Faulty gauge replaced. Rain-measure issued. 2003 Fair exposure. Gauge in good order and records up to date. Good station. 2005 Fair exposure. Gauge in good order and records up to date. 2009 Fair exposure. Faulty gauge replaced. 2011 Fair exposure. Gauge in good order and records up to date.	
Shannon, Clare	Rebogue Engine Station, Limerick 1861-1879 CF 1.16 - Ennis Clare 1875-1895 CF 0.97 10 inch square gauge 3ft 2 inch above ground ALT 21 - Foynes, Coonanes 1914-1915 5 inch gauge 1ft above ground ALT 50 - 1916-1930 8 inch gauge 1ft above ground ALT 50 - 1931-1933 5 inch gauge 1ft above ground ALT 50 - 1914-1918 8 inch gauge 1ft above ground ALT 50 - Victoria Terrace, Limerick 1895-1905 5 inch gauge 1ft above ground ALT 60 - 1906-1913 5 inch gauge 1ft above ground, ALT 52 - 1914-1918 5 inch gauge 1ft above ground, ALT 51 - Shannon Airport 1941- onwards - Nenagh Castle Lough 1875 - 1961 - Knightsown, Valentia Island 1861-1865 CF 1.025 8 inch gauge 2ft 6 inch above ground ALT 38 - Valentia Observatory, Valentia Island 1866-1875 CF1.025 8 inch gauge 1 ft above ground ALT11-1876-1879 CF1.025 8 inch gauge 2 ft above ground ALT 12-1880-1892 1.025 11 inch gauge 2 ft above ground ALT 11	Constructed by Tabony 1980. 1906 Moved to George Street. 1909 Dr Mills report .In small garden at safe distance from houses and walls. The Limerick Rebogue records are supported by a second gauge kept there. Ennis is used as intermediate station to find the ratio between Rebogue and Foynes. Similar results could have been obtained using Jane Ville or Newcastle West. Shannon and Foynes being opposite side of estuary are assumed to have same average annual rainfall.

Station name and County	***Composite Stations, Period ,Correction factors ,Gauge Diameter-Rim height above ground ,altitude above sea level in feet***	***Notes***
Enniscorthy, Wexford	Enniscorthy, Ballyhyland 1870-1890 CF 1.2 - Enniscorthy, Ballyhyland. 1891-1894 CF 0.9 - Enniscorthy, Ballyhyland 1895-1901 CF 1.2 - Enniscorthy, Woodbrook 1902-1942 CF 0.89 -Waterford (Tabony) 1943-1943 CF 1.19 - Enniscorthy, Woodbrook 1944-1945 CF 0.88 - Waterford (Tabony) 1946-1958 CF 1.19 - Enniscorthy, Woodbrook. 1959-1980 CF 1 - Enniscorthy, Brownswood 1983-2013 Winter CF 0.74, Spring CF 0.75, Summer CF 0.83, Autumn CF 0.83.	Constructed by Briffa (1984) using the 10 year sheets of the rainfall Archives of the UK Met Office before 1940 and post 1940 from the Irish Met service. Also records from Tabony were used for certain periods. Update in Jones and Conway 1997 up to 1994 using data from Met Eireann. Enniscorthy was updated from Enniscorthy, Brownswood stno 4015 from 1994-2010 for this research.

Appendix 2 Supplementary drought information for chapter 4

This appendix provides tables listing details of all drought events identified using the SPI-12 index for the Island of Ireland (IoI) composite series (1850-2015); the Island of Ireland extended (IoIext) series (1765-1849) and each of the 25 stations in the Island of Ireland Precipitation Network (IIP) (1850-2015). IoI and IoIext series are presented first and followed by tables for individual stations in alphabetical order. All droughts are presented in chronological order. Please see paper for details on how individual drought events were identified and on how event statistics were derived.

Table 1: Island of Ireland (IoI) composite series (1850-2015);. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified in the IoI composite series. (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-0.68	-6.81	10	-1.16
1854-04	1860-05	-1.34	-97.54	73	-2.84
1864-10	1865-08	-0.94	-9.40	10	-1.6
1868-07	1868-12	-1.02	-5.10	5	-1.37
1870-04	1871-07	-1.07	-15.99	15	-2.04
1874-01	1875-01	-1.15	-13.81	12	-1.86
1880-06	1881-06	-0.67	-8.02	12	-1.79
1885-03	1885-10	-0.82	-5.71	7	-1.26
1887-07	188902	-1.54	-29.29	19	-3.14
1889-07	188910	-0.72	-2.15	3	-1.19
1890-10	1892-02	-1.10	-17.64	16	-1.94
1893-08	1894-11	-1.14	-17.08	15	-2.47
1895-05	1896-09	-0.73	-11.72	16	-1.41
1902-10	1903-02	-0.64	-2.55	4	-1.08
1905-02	1908-02	-1.15	-41.48	36	-2.07
1909-08	1910-08	-0.75	-9.05	12	-1.87
1911-06	1912-01	-1.45	-10.16	7	-2.27
1914-06	1914-08	-0.84	-1.67	2	-1.10
1918-08	1918-09	-1.01	-1.01	1	-1.01
1919-10	1920-07	-1.05	-9.44	9	-1.63
1921-06	1923-10	-1.00	-27.86	28	-1.67
1927-02	1927-09	-0.68	-4.75	7	-1.09
1932-11	1933-03	-0.78	-3.11	4	-1.42
1933-09	1934-12	-2.10	-31.55	15	-3.12
1938-03	1938-11	-1.20	-9.58	8	-2.11
1941-12	1942-09	-0.85	-7.69	9	-1.31
1942-11	1943-11	-0.47	-5.61	12	-1.08
1944-03	1945-02	-1.15	-12.67	11	-1.82
1949-12	1950-07	-0.58	-4.03	7	-1.01
1952-09	1954-05	-1.49	-29.74	20	-2.59
1955-11	1957-02	-0.99	-14.91	15	-2.45
1959-08	1960-02	-1.34	-8.01	6	-2.51
1963-01	1963-11	-0.89	-8.92	10	-1.46
1964-11	1965-01	-0.68	-1.35	2	-1.06
1969-12	1970-11	-1.15	-12.62	11	-1.70
1971-02	1974-02	-1.12	-40.47	36	-2.24
1975-06	1977-02	-1.55	-30.98	20	-2.42
1985-01	1985-06	-0.78	-3.91	5	-1.21
1989-09	1990-02	-0.84	-4.20	5	-1.13
1991-02	1991-04	-0.76	-1.51	2	-1.06
1992-02	1992-09	-0.95	-6.67	7	-1.29
1997-03	1997-09	-0.86	-5.18	6	-1.47
2001-12	2002-05	-0.52	-2.58	5	-1.46
2003-11	2004-10	-1.16	-12.81	11	-1.60
2006-04	2006-11	-0.73	-5.08	7	-1.11

Table 2: Island of Ireland extended (IoIext) series (1765-1849). Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified in the IoIext series. (1765-1849)

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1778-05	1779-09	-0.78	-12.41	16	-1.44
1780-12	1782-05	-1.03	-17.59	17	-1.58
1784-02	1786-03	-1.02	-25.61	25	-2.43
1788-11	1789-10	-0.92	-10.13	11	-2.08
1794-01	1794-11	-0.90	-9.05	10	-1.28
1797-01	1797-08	-0.51	-3.56	7	-1.03
1800-09	1804-10	-1.05	-51.33	49	-2.13
1805-01	1806-12	-1.27	-29.25	23	-2.30
1807-03	1809-01	-0.96	-21.03	22	-1.78
1810-09	1810-12	-0.80	-2.41	3	-1.33
1813-09	1815-03	-1.59	-28.54	18	-2.59
1821-08	1821-12	-0.78	-3.12	4	-1.22
1826-05	1827-10	-1.25	-21.23	17	-2.40
1830-01	1830-06	-0.80	-3.98	5	-1.09
1831-09	1831-12	-0.82	-2.45	3	-1.50
1832-11	1834-01	-1.04	-14.54	14	-1.47
1834-12	1836-01	-1.06	-13.73	13	-2.18
1838-01	1839-09	-0.86	-17.18	20	-1.76
1840-12	1841-10	-0.90	-9.01	10	-1.57
1842-10	1843-08	-1.04	-10.39	10	-1.88
1844-11	1845-12	-1.02	-13.26	13	-1.70
1847-08	1848-02	-1.39	-8.32	6	-1.85
1849-08	1849-12	-0.65	-3.27	5	-1.08

Table 3: Ardara. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Ardara (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-01	1860-05	-1.38	-105.02	76	-2.79
1861-06	1861-09	-0.83	-2.49	3	-1.39
1864-10	1865-08	-0.59	-5.89	10	-1.16
1868-07	1869-02	-0.86	-6.02	7	-1.52
1870-09	1871-07	-0.78	-7.82	10	-1.46
1874-01	1874-12	-0.93	-10.21	11	-1.34
1876-01	1876-03	-0.70	-1.39	2	-1.06
1880-09	1881-10	-1.37	-17.79	13	-2.63
1885-12	1886-12	-0.69	-8.33	12	-1.12
1887-06	1889-10	-1.14	-31.84	28	-2.09
1891-11	1894-01	-0.65	-16.89	26	-2.02
1895-02	1896-06	-1.38	-22.02	16	-2.43
1900-04	1903-08	-0.93	-37.35	40	-2.53
1905-12	1906-10	-0.50	-4.99	10	-1.13
1911-05	1913-01	-0.98	-19.53	20	-2.36
1915-09	1916-06	-0.94	-8.45	9	-1.29
1921-05	1922-06	-1.04	-13.52	13	-2.15
1925-12	1926-11	-0.71	-7.76	11	-1.14
1929-03	1934-12	-1.43	-98.35	69	-4.14
1938-02	1938-10	-1.18	-9.43	8	-1.61
1939-12	1940-09	-0.76	-6.80	9	-1.24
1941-12	1942-01	-1.22	-1.22	1	-1.22
1944-08	1944-11	-0.58	-1.74	3	-1.15
1953-01	1953-11	-1.84	-18.41	10	-2.71
1955-11	1957-01	-1.38	-19.33	14	-2.28
1959-08	1960-02	-1.20	-7.19	6	-2.12
1963-01	1963-11	-1.28	-12.80	10	-1.99
1964-11	1965-01	-0.95	-1.89	2	-1.40
1969-10	1970-07	-0.77	-6.89	9	-1.24
1971-09	1974-08	-0.98	-34.34	35	-2.23
1975-09	1976-07	-1.11	-11.13	10	-1.81
1979-03	1979-10	-0.58	-4.05	7	-1.31
1984-10	1985-08	-0.88	-8.76	10	-1.66
1989-09	1990-02	-0.36	-1.80	5	-1.09
1993-11	1994-02	-0.51	-1.52	3	-1.24
1996-02	1997-03	-1.24	-16.11	13	-2.14
2001-12	2002-03	-0.80	-2.41	3	-1.52
2003-06	2004-09	-0.89	-13.41	15	-1.57
2006-01	2006-12	-1.35	-14.88	11	-1.75
2010-08	2011-05	-0.77	-6.90	9	-1.23

Table 4: Armagh. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit, maximum intensity (min. SPI-12) for each event identified at Armagh (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1851-05	1852-06	-0.90	-11.68	13	-1.29
1854-04	1854-07	-0.60	-1.81	3	-1.16
1855-07	1857-04	-1.93	-40.59	21	-2.81
1858-03	1860-08	-1.04	-30.20	29	-1.80
1860-12	1861-09	-0.92	-8.31	9	-1.45
1863-07	1863-11	-0.74	-2.96	4	-1.27
1864-10	1865-05	-0.73	-5.08	7	-1.72
1868-07	1871-07	-1.59	-57.29	36	-4.35
1871-12	1872-06	-0.57	-3.45	6	-1.03
1873-12	1875-09	-1.27	-26.59	21	-2.62
1876-10	1877-01	-1.15	-3.46	3	-1.70
1879-01	1879-07	-1.06	-6.39	6	-1.33
1885-07	1886-10	-1.00	-14.94	15	-1.77
1887-10	1889-05	-1.30	-24.67	19	-2.94
1889-06	1889-10	-0.76	-3.06	4	-1.48
1890-05	1892-08	-0.90	-24.33	27	-1.77
1893-08	1894-06	-1.41	-14.07	10	-2.54
1895-02	1896-06	-0.86	-13.81	16	-2.09
1906-08	1907-06	-1.02	-10.16	10	-1.54
1909-09	1910-02	-0.86	-4.29	5	-1.24
1911-06	1912-03	-1.57	-14.16	9	-2.59
1914-10	1915-01	-0.86	-2.59	3	-1.42
1919-11	1920-04	-0.74	-3.71	5	-1.50
1921-10	1922-09	-0.68	-7.49	11	-1.26
1927-05	1927-09	-0.94	-3.78	4	-1.06
1933-09	1934-12	-2.30	-34.51	15	-3.79
1938-02	1938-10	-1.15	-9.18	8	-2.20
1944-02	1944-11	-1.07	-9.61	9	-1.51
1946-05	1946-09	-1.29	-5.16	4	-1.59
1953-01	1954-03	-1.48	-20.71	14	-2.24
1956-05	1956-08	-1.51	-4.54	3	-1.88
1964-11	1965-01	-0.70	-1.40	2	-1.06
1971-10	1974-09	-0.98	-34.14	35	-2.18
1975-06	1977-02	-1.76	-35.29	20	-3.04
1978-02	1979-05	-0.96	-14.39	15	-1.42
1983-11	1984-02	-0.97	-2.92	3	-1.18
1984-05	1984-11	-0.50	-2.97	6	-1.09
1985-02	1985-08	-0.88	-5.26	6	-1.53
1987-05	1987-10	-0.79	-3.96	5	-1.22
1989-07	1990-11	-0.79	-12.72	16	-1.62
1991-08	1992-08	-1.33	-15.99	12	-1.82
1995-07	1995-11	-1.29	-5.16	4	-1.75
1996-03	1996-05	-0.73	-1.46	2	-1.06
1997-01	1998-01	-1.09	-13.13	12	-1.84
2001-12	2002-05	-0.89	-4.45	5	-1.83
2003-11	2004-10	-1.47	-16.13	11	-2.16
2006-01	2006-12	-0.94	-10.32	11	-1.44
2009-03	2009-05	-0.66	-1.32	2	-1.04
2011-09	2011-10	-1.13	-1.13	1	-1.13

Table 5: Athboy. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Athboy (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-03	1860-06	-1.16	-86.64	75	-2.10
1863-07	1866-01	-0.76	-22.83	30	-2.04
1868-07	1869-02	-0.91	-6.40	7	-1.14
1870-04	1871-07	-1.09	-16.28	15	-2.08
1874-01	1875-01	-1.14	-13.72	12	-1.17
1880-09	1880-12	-0.79	-2.37	3	-1.29
1884-11	1886-11	-0.68	-16.43	24	-1.45
1887-07	1889-02	-1.33	-25.34	19	-2.85
1889-07	1889-10	-0.67	-2.02	3	-1.18
1890-05	1896-09	-1.53	-116.21	76	-3.29
1901-12	1903-03	-0.74	-11.09	15	-1.20
1905-01	1908-01	-1.36	-48.79	36	-2.25
1911-08	1912-01	-0.86	-4.28	5	-1.58
1914-05	1914-08	-1.30	-3.90	3	-1.58
1919-10	1920-05	-0.75	-5.24	7	-1.29
1926-05	1926-11	-0.82	-4.91	6	-1.61
1933-09	1935-11	-1.55	-40.36	26	-2.97
1938-03	1939-02	-0.83	-9.12	11	-1.82
1939-10	1940-05	-0.93	-6.51	7	-1.66
1944-05	1944-11	-0.96	-5.75	6	-1.33
1949-09	1950-08	-0.71	-7.79	11	-1.21
1953-01	1954-05	-1.35	-21.64	16	-2.13
1956-02	1957-03	-0.95	-12.40	13	-2.50
1959-08	1960-01	-1.28	-6.41	5	-2.24
1963-09	1963-11	-1.01	-2.01	2	-1.18
1964-11	1964-12	-1.01	-1.01	1	-1.01
1969-12	1970-11	-1.42	-15.60	11	-1.99
1971-04	1974-03	-1.27	-44.28	35	-2.47
1975-07	1977-04	-0.92	-19.38	21	-1.37
1978-10	1978-12	-1.22	-2.44	2	-1.24
1989-07	1990-02	-0.77	-5.37	7	-1.08
1995-09	1995-11	-0.68	-1.35	2	-1.02
1997-04	1998-01	-0.40	-3.61	9	-1.03
2001-12	2002-05	-0.72	-3.59	5	-1.78
2003-11	2004-10	-0.99	-10.88	11	-1.79
2005-10	2006-12	-1.41	-19.78	14	-2.03

Table 6: Birr. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Birr (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1850-12	1852-08	-0.83	-16.55	20	-1.22
1854-04	1856-12	-1.25	-39.85	32	-2.42
1857-12	1860-05	-1.24	-36.03	29	-2.07
1863-06	1865-08	-1.11	-28.86	26	-2.04
1868-07	1868-12	-0.74	-3.69	5	-1.14
1870-08	1871-07	-0.99	-10.94	11	-1.79
1871-10	1872-09	-0.75	-8.27	11	-1.17
1884-10	1885-09	-1.03	-11.28	11	-1.48
1887-06	1890-11	-1.26	-51.73	41	-2.97
1891-01	1891-08	-1.11	-7.79	7	-1.70
1893-09	1894-04	-0.77	-5.40	7	-1.41
1895-05	1896-09	-1.10	-17.66	16	-1.73
1902-09	1903-03	-1.06	-6.37	6	-1.40
1905-05	1906-10	-1.21	-20.59	17	-1.80
1909-09	1910-02	-0.76	-3.81	5	-1.34
1911-04	1912-03	-1.20	-13.23	11	-2.31
1914-06	1915-01	-0.64	-4.48	7	-1.13
1918-08	1918-12	-0.70	-2.78	4	-1.38
1919-10	1920-03	-0.83	-4.14	5	-1.20
1921-10	1923-10	-0.49	-11.78	24	-1.08
1926-04	1928-01	-0.60	-12.57	21	-1.65
1932-08	1934-12	-1.13	-31.69	28	-2.28
1938-04	1938-07	-0.84	-2.53	3	-1.12
1942-02	1942-08	-0.75	-4.47	6	-1.01
1953-01	1954-03	-1.12	-15.68	14	-1.78
1956-02	1956-10	-1.14	-9.09	8	-2.31
1959-08	1959-12	-1.35	-5.38	4	-2.10
1963-09	1965-01	-0.68	-10.93	16	-1.81
1969-09	1974-02	-1.44	-76.21	53	-2.88
1975-08	1977-08	-1.55	-37.25	24	-2.42
1978-08	1980-01	-0.94	-16.05	17	-1.72
1982-07	1982-11	-0.63	-2.51	4	-1.06
1985-01	1985-08	-1.21	-8.44	7	-1.82
1987-08	1988-03	-0.65	-4.53	7	-1.39
1989-07	1991-08	-0.83	-20.64	25	-1.58
1996-02	1996-08	-0.50	-3.02	6	-1.08
1997-03	1997-07	-0.88	-3.53	4	-1.26
2001-11	2002-05	-0.81	-4.84	6	-1.78
2003-10	2005-05	-1.67	-31.73	19	-3.13
2006-01	2006-09	-0.94	-7.54	8	-1.41

2013-11	2014-02	-0.62	-1.86	3	-1.13

Table 7: Cappoquinn. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Cappoquinn (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-0.90	-8.97	10	-1.34
1854-10	1860-06	-1.01	-68.53	68	-3.09
1864-10	1865-08	-0.87	-8.69	10	-1.45
1868-07	1868-12	-0.63	-3.14	5	-1.01
1870-09	1871-04	-0.74	-5.15	7	-1.53
1874-07	1875-01	-1.23	-7.38	6	-1.77
1880-08	1881-08	-0.60	-7.24	12	-1.69
1885-03	1885-09	-0.52	-3.09	6	-1.09
1887-09	1888-07	-1.67	-16.65	10	-2.45
1891-03	1891-12	-0.77	-6.95	9	-1.25
1893-10	1894-11	-0.80	-10.37	13	-1.65
1902-01	1902-07	-0.67	-4.03	6	-1.40
1905-10	1907-12	-0.65	-16.83	26	-1.46
1909-09	191008	-1.00	-11.02	11	-1.59
1911-08	1912-01	-0.94	-4.70	5	-1.43
1914-11	1914-12	-1.20	-1.20	1	-1.20
1918-08	1918-12	-0.59	-2.36	4	-1.34
1919-10	1920-10	-1.03	-12.30	12	-1.76
1921-07	1923-11	-1.55	-43.26	28	-3.01
1926-10	1927-12	-1.22	-17.02	14	-2.39
1932-11	1933-02	-0.70	-2.11	3	-1.33
1933-12	1935-11	-1.21	-27.78	23	-2.48
1938-03	1938-11	-1.01	-8.04	8	-1.70
1942-02	1943-11	-0.70	-14.74	21	-1.72
1944-01	1945-06	-1.21	-20.51	17	-2.27
1945-11	1946-08	-0.36	-3.28	9	-1.13
1949-12	1950-08	-0.92	-7.34	8	-1.73
1952-09	1954-10	-1.25	-31.34	25	-2.40
1956-02	1957-02	-0.80	-9.62	12	-1.93
1959-09	1960-02	-0.97	-4.86	5	-1.78
1962-02	1964-01	-0.82	-18.80	23	-1.37
1967-04	1969-01	-0.63	-13.29	21	-1.28
1969-11	1974-08	-1.05	-60.11	57	-2.21
1975-02	1977-02	-1.44	-34.53	24	-2.10
1989-08	1993-06	-0.96	-44.26	46	-2.00
1997-03	1997-12	-0.97	-8.69	9	-1.79
1999-11	2000-11	-1.12	-13.43	12	-1.41

2003-12	2004-10	-1.02	-10.16	10	-1.90
2005-08	2007-02	-0.93	-16.67	18	-1.40
2008-02	2008-10	-0.93	-7.46	8	-1.37
2011-04	2012-08	-1.50	-24.06	16	-2.40
2015-04	2015-12	-0.77	-6.18	8	-1.32

Table 8: Cork Airport. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Cork Airport (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-1.30	-12.99	10	-1.60
1854-10	1857-07	-1.52	-50.05	33	-3.83
1864-10	1865-08	-0.74	-7.42	10	-1.27
1867-12	1868-11	-0.88	-9.67	11	-1.59
1870-05	1871-07	-0.82	-11.49	14	-1.42
1874-03	1875-01	-1.52	-15.19	10	-2.31
1880-09	1880-11	-0.79	-1.57	2	-1.04
1885-03	1885-09	-0.58	-3.46	6	-1.14
1887-07	1888-11	-1.72	-27.56	16	-2.74
1889-12	1892-02	-0.90	-23.31	26	-1.93
1893-11	1894-11	-0.90	-10.79	12	-1.50
1896-12	1897-04	-1.06	-4.23	4	-1.60
1899-10	1899-12	-1.21	-2.43	2	-1.24
1902-10	1902-11	-1.02	-1.02	1	-1.02
1905-02	1906-01	-0.66	-7.30	11	-1.45
1906-08	1912-03	-1.29	-86.54	67	-3.03
1913-02	1914-12	-0.85	-18.62	22	-1.88
1917-11	1918-11	-0.71	-8.51	12	-1.58
1919-11	1920-07	-1.15	-9.19	8	-1.71
1921-06	1923-11	-0.92	-26.77	29	-2.24
1927-01	1927-12	-1.03	-11.30	11	-1.64
1932-11	1934-12	-1.26	-31.56	25	-2.21
1938-03	1939-02	-1.11	-12.21	11	-2.19
1942-11	1943-10	-0.89	-9.78	11	-1.68
1944-01	1945-03	-1.28	-17.89	14	-1.92
1949-12	1950-09	-0.67	-6.05	9	-1.60
1952-09	1954-03	-1.45	-26.11	18	-2.37
1959-09	1960-07	-0.64	-6.39	10	-1.99
1962-02	1963-11	-0.69	-14.43	21	-1.49
1970-01	1972-05	-1.11	-31.19	28	-1.72
1972-10	1973-10	-0.83	-9.93	12	-1.36
1975-04	1977-01	-1.49	-31.26	21	-2.51
1985-01	1985-08	-0.50	-3.47	7	-1.06

1989-10	1990-01	-0.99	-2.96	3	-1.40
1991-01	1991-11	-0.81	-8.14	10	-1.66
1992-03	1993-06	-0.89	-13.38	15	-1.54
2000-08	2001-02	-0.63	-3.77	6	-1.45
2003-12	2004-10	-1.17	-11.71	10	-1.82
2006-07	2006-12	-0.80	-4.00	5	-1.07
2010-11	2012-08	-1.25	-26.32	21	-1.92

Table 9: Derry. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Derry (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-01	1860-05	-1.36	-103.24	76	-2.75
1861-05	1861-11	-1.07	-6.42	6	-1.84
1865-06	1866-04	-0.58	-5.79	10	-1.25
1868-07	1869-11	-0.71	-11.31	16	-1.84
1870-12	1871-07	-0.88	-6.13	7	-1.21
1874-01	1874-12	-0.99	-10.90	11	-1.37
1875-12	1876-04	-1.15	-4.60	4	-1.97
1880-01	1881-06	-1.29	-21.89	17	-2.37
1885-12	1886-12	-0.75	-8.96	12	-1.17
1887-05	1889-02	-1.48	-31.00	21	-2.66
1889-07	1889-10	-0.62	-1.87	3	-1.21
1890-10	1890-11	-1.39	-1.39	1	-1.39
1891-02	1892-02	-0.82	-9.82	12	-1.38
1893-11	1894-02	-0.97	-2.90	3	-1.35
1895-02	1896-03	-1.81	-23.54	13	-2.56
1898-08	1899-09	-0.57	-7.45	13	-1.12
1905-07	1907-06	-1.00	-22.92	23	-1.65
1908-08	1910-02	-0.63	-11.30	18	-1.23
1911-06	1912-06	-1.87	-22.42	12	-2.47
1914-01	1914-03	-0.76	-1.52	2	-1.29
1914-06	1916-05	-0.99	-22.67	23	-1.67
1919-10	1920-05	-0.85	-5.92	7	-1.37
1921-04	1922-08	-1.24	-19.90	16	-2.10
1922-12	1923-10	-1.10	-11.04	10	-1.63
1929-03	1930-03	-1.07	-12.87	12	-1.97
1932-02	1934-12	-2.03	-68.99	34	-4.38
1938-04	1938-10	-0.88	-5.28	6	-1.22
1940-07	1940-12	-0.64	-3.22	5	-1.09
1941-12	1942-01	-1.28	-1.28	1	-1.28
1944-08	1944-11	-0.61	-1.84	3	-1.18
1953-03	1954-03	-0.79	-9.48	12	-1.40
1955-12	1956-08	-1.68	-13.47	8	-2.50
1959-07	1960-07	-1.25	-15.04	12	-2.84
1963-01	1963-08	-1.08	-7.55	7	-1.71

1964-07	1965-04	-0.64	-5.78	9	-1.41
1969-09	1970-09	-0.86	-10.35	12	-2.03
1972-09	1974-09	-1.18	-28.37	24	-2.31
1975-12	1977-02	-1.21	-16.96	14	-1.88
1978-11	1979-05	-0.76	-4.58	6	-1.12
1985-02	1985-06	-0.81	-3.22	4	-1.29
1989-09	1990-02	-0.59	-2.93	5	-1.00
1996-03	1996-08	-0.70	-3.52	5	-1.13
1997-01	1997-12	-0.69	-7.57	11	-1.36
2001-11	2002-05	-0.70	-4.21	6	-1.80
2003-10	2004-10	-1.29	-15.49	12	-1.82
2006-01	2006-12	-1.01	-11.13	11	-1.38

Table 10: Drumnsa. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Drumnsa (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-03	1860-05	-1.00	-74.17	74	-2.21
1868-10	1868-12	-0.84	-1.67	2	-1.09
1870-09	1871-07	-0.60	-6.00	10	-1.45
1880-09	1881-10	-0.51	-6.60	13	-1.32
1887-10	1890-11	-0.76	-28.10	37	-2.27
1891-02	1892-02	-0.91	-10.96	12	-1.35
1893-10	1896-09	-1.03	-35.91	35	-2.26
1899-09	1900-10	-0.75	-9.75	13	-1.15
1905-10	1908-04	-0.71	-21.31	30	-1.17
1909-06	1910-06	-1.20	-14.39	12	-2.34
1911-07	1912-03	-1.43	-11.43	8	-2.55
1915-03	1916-05	-1.06	-14.84	14	-1.79
1919-09	1920-07	-1.00	-9.99	10	-2.02
1921-02	1924-07	-1.13	-46.29	41	-2.29
1925-08	1928-11	-1.12	-43.76	39	-2.03
1929-03	1931-04	-1.74	-43.49	25	-3.67
1932-05	1933-06	-0.96	-12.48	13	-1.69
1933-09	1936-01	-1.37	-38.36	28	-3.27
1937-11	1938-11	-1.59	-19.10	12	-2.41
1941-06	1942-09	-1.35	-20.32	15	-1.80
1942-11	1943-02	-0.69	-2.08	3	-1.27
1952-09	1954-03	-1.49	-26.81	18	-2.42
1956-05	1956-10	-1.04	-5.22	5	-2.15
1959-07	1960-02	-1.29	-9.06	7	-2.35
1963-01	1965-05	-0.94	-26.29	28	-1.56
1967-04	1969-08	-1.50	-42.04	28	-2.72
1970-01	1970-09	-0.66	-5.31	8	-1.38

1971-09	1974-01	-0.89	-24.89	28	-1.91
1975-09	1976-07	-1.07	-10.71	10	-1.59
1979-03	1979-05	-1.04	-2.07	2	-1.35
1985-01	1985-05	-0.97	-3.87	4	-1.44
1992-04	1992-08	-0.80	-3.20	4	-1.04
2001-12	2002-02	-1.13	-2.26	2	-1.51
2004-05	2004-10	-0.70	-3.49	5	-1.06
2006-01	2006-10	-0.45	-4.03	9	-1.02

Table 11: Dublin Airport. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Dublin Airport (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-06	-0.96	-4.82	5	-1.24
1854-04	1860-07	-1.12	-83.87	75	-2.39
1863-05	1864-03	-0.75	-7.53	10	-1.83
1864-09	1865-12	-1.02	-15.37	15	-1.97
1868-03	1869-05	-1.31	-18.35	14	-2.46
1870-05	1871-04	-1.08	-11.90	11	-1.79
1884-09	1886-11	-1.30	-33.79	26	-2.42
1887-05	1889-01	-1.82	-36.48	20	-3.54
1889-07	1889-10	-0.59	-1.76	3	-1.40
1890-10	1892-02	-1.21	-19.36	16	-1.87
1893-09	1894-08	-1.11	-12.23	11	-1.82
1899-11	1900-02	-0.62	-1.86	3	-1.06
1902-01	1902-07	-0.71	-4.29	6	-1.03
1904-10	1908-01	-1.30	-50.79	39	-2.65
1908-12	1910-02	-1.06	-14.84	14	-1.57
1911-06	1912-07	-1.04	-13.51	13	-1.86
1913-08	1914-12	-0.74	-11.81	16	-1.82
1922-05	1923-11	-1.02	-18.37	18	-1.99
1929-06	1930-01	-0.98	-6.83	7	-1.47
1933-09	1935-06	-1.49	-31.25	21	-2.95
1938-03	1939-02	-1.01	-11.09	11	-2.06
1944-05	1945-06	-0.80	-10.41	13	-1.86
1945-11	1946-08	-0.92	-8.24	9	-1.75
1949-07	1950-09	-1.03	-14.38	14	-1.72
1953-01	1954-11	-0.92	-20.19	22	-1.50
1956-06	1956-08	-0.66	-1.32	2	-1.07
1959-09	1960-02	-1.03	-5.17	5	-1.99
1962-01	1965-01	-0.77	-27.74	36	-1.43
1970-05	1971-06	-0.63	-8.20	13	-1.48
1971-11	1974-02	-0.99	-26.61	27	-2.16

1975-06	1977-02	-1.13	-22.66	20	-1.73
1978-02	1978-12	-0.99	-9.95	10	-1.36
1989-01	1991-01	-1.25	-29.92	24	-2.08
1992-02	1993-06	-1.11	-17.81	16	-1.72
2004-06	2004-10	-0.69	-2.77	4	-1.30
2011-09	2012-05	-0.53	-4.21	8	-1.34

Table 12: Enniscorthy. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Enniscorthy (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-0.89	-8.91	10	-1.43
1854-10	1860-06	-0.98	-66.88	68	-2.99
1864-10	1865-08	-0.88	-8.84	10	-1.58
1868-07	1868-12	-0.67	-3.37	5	-1.08
1870-05	1871-09	-1.20	-19.12	16	-1.91
1874-03	1875-09	-1.17	-21.07	18	-2.50
1878-12	1879-08	-0.54	-4.28	8	-1.19
1880-09	1880-12	-0.69	-2.07	3	-1.38
1884-11	1885-10	-0.65	-7.14	11	-1.10
1887-09	1888-12	-1.36	-20.47	15	-2.65
1889-07	1890-03	-0.56	-4.50	8	-1.01
1891-03	1895-08	-1.24	-65.57	53	-3.34
1896-08	1896-10	-0.61	-1.22	2	-1.05
1904-12	1908-03	-1.66	-64.57	39	-2.86
1909-09	1911-12	-0.86	-23.24	27	-1.55
1914-05	1915-10	-0.69	-11.71	17	-1.40
1917-11	1918-12	-0.68	-8.78	13	-1.30
1919-11	1920-10	-0.78	-8.56	11	-1.38
1921-07	1924-01	-0.99	-29.60	30	-1.74
1927-01	1927-09	-0.63	-5.03	8	-1.16
1932-11	1933-03	-0.78	-3.12	4	-1.45
1934-06	1934-12	-1.02	-6.11	6	-1.74
1935-12	1936-02	-0.69	-1.38	2	-1.12
1938-03	1938-11	-1.30	-10.43	8	-2.37
1941-04	1946-09	-1.24	-80.51	65	-2.70
1949-12	1950-09	-0.56	-5.05	9	-1.27
1953-01	1954-12	-1.08	-24.76	23	-2.07
1956-05	1956-10	-0.98	-4.91	5	-1.89
1959-09	1960-05	-0.75	-5.98	8	-1.59
1962-02	1962-08	-0.65	-3.91	6	-1.18
1969-11	1970-11	-1.11	-13.32	12	-1.61
1971-02	1972-11	-0.95	-19.94	21	-2.13
1973-06	1974-01	-0.70	-4.87	7	-1.26

1975-09	1977-02	-1.46	-24.77	17	-2.18
1984-09	1985-06	-0.65	-5.86	9	-1.34
1989-10	1990-01	-0.70	-2.10	3	-1.01
1991-02	1991-11	-0.38	-3.42	9	-1.25
1992-06	1993-05	-0.68	-7.45	11	-1.19
1995-09	1996-01	-0.74	-2.96	4	-1.04
1997-03	1997-09	-0.91	-5.44	6	-1.59
2000-01	2000-11	-0.89	-8.93	10	-1.39
2004-07	2005-11	-0.72	-11.48	16	-1.43
2012-02	2012-07	-0.99	-4.93	5	-1.48
2015-11	2015-12	-1.00	-1.00	1	-1.00

Table 13: Foulkesmills. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Foulkesmills (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-0.78	-7.75	10	-1.33
1854-10	1860-06	-0.99	-67.04	68	-2.77
1864-10	1865-08	-0.82	-8.24	10	-1.51
1868-07	1868-12	-0.69	-3.47	5	-1.17
1870-07	1871-07	-0.83	-9.96	12	-1.55
1874-06	1875-01	-1.47	-10.31	7	-1.10
1878-12	1879-09	-0.68	-6.11	9	-1.28
1880-06	1881-06	-0.70	-8.39	12	-1.85
1884-10	1885-10	-1.03	-12.35	12	-1.60
1887-09	1888-12	-1.76	-26.36	15	-2.95
1889-07	1891-12	-1.04	-30.02	29	-2.24
1893-07	1894-11	-1.34	-21.46	16	-2.48
1896-08	1897-03	-0.71	-4.94	7	-1.22
1905-02	1908-01	-1.34	-46.84	35	-2.61
1914-05	1914-08	-0.88	-2.64	3	-1.12
1917-11	1918-10	-0.60	-6.63	11	-1.12
1919-11	1920-07	-0.80	-6.42	8	-1.25
1921-10	1923-11	-0.82	-20.47	25	-1.60
1934-02	1934-12	-1.32	-13.18	10	-1.86
1938-03	1938-10	-1.01	-7.05	7	-1.85
1942-11	1943-10	-0.39	-4.33	11	-1.36
1944-05	1945-02	-0.98	-8.86	9	-1.46
1949-09	1950-09	-1.08	-13.01	12	-1.97
1952-12	1954-11	-0.98	-22.50	23	-1.78
1956-05	1956-09	-0.96	-3.84	4	-1.61
1959-08	1960-07	-0.96	-10.61	11	-2.27
1963-01	1963-11	-0.61	-6.11	10	-1.36
1964-11	1965-11	-0.86	-10.26	12	-1.25

1969-12	1974-02	-1.13	-56.33	50	-2.21
1975-02	1977-02	-2.04	-49.05	24	-3.04
1984-08	1985-06	-0.74	-7.39	10	-1.36
1989-07	1993-05	-1.12	-51.40	46	-1.99
1995-08	1996-03	-1.04	-7.25	7	-1.54
1997-03	1997-12	-1.26	-11.38	9	-2.39
1999-06	2000-11	-1.18	-20.13	17	-1.61
2001-12	2002-05	-0.61	-3.06	5	-1.04
2004-07	2004-10	-0.81	-2.43	3	-1.41
2005-02	2006-03	-0.45	-5.87	13	-1.06
2011-05	2012-08	-1.15	-17.21	15	-2.02

Table 14: Killarney. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Killarney (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-1.22	-12.20	10	-1.56
1854-10	1859-11	-1.11	-67.99	61	-3.14
1864-12	1865-10	-0.63	-6.25	10	-1.02
1870-09	1871-07	-0.52	-5.21	10	-1.17
1880-06	1881-12	-0.71	-12.72	18	-1.41
1886-02	1886-10	-0.67	-5.39	8	-1.09
1887-11	1889-02	-1.21	-18.13	15	-2.39
1891-02	1892-02	-1.20	-14.34	12	-1.91
1893-08	1894-05	-1.35	-12.11	9	-2.40
1902-01	1903-02	-0.87	-11.28	13	-1.69
1905-02	1908-03	-1.02	-37.76	37	-2.01
1909-08	1910-03	-1.13	-7.93	7	-1.91
1911-03	1911-12	-0.83	-7.43	9	-1.02
1919-10	1920-07	-0.85	-7.68	9	-1.61
1921-06	1923-10	-0.71	-19.92	28	-1.69
1929-04	1930-01	-1.02	-9.14	9	-1.50
1933-12	1934-12	-1.70	-20.42	12	-2.53
1935-09	1937-02	-0.84	-14.33	17	-1.66
1939-10	1942-09	-1.20	-42.06	35	-1.91
1942-11	1943-11	-1.06	-12.70	12	-1.56
1944-02	1945-05	-1.57	-23.56	15	-2.56
1952-12	1954-03	-1.36	-20.47	15	-2.24
1955-10	1957-02	-1.55	-24.80	16	-2.42
1959-02	1959-12	-1.00	-10.00	10	-2.34
1962-10	1966-05	-0.95	-40.72	43	-2.08
1969-11	1972-12	-1.28	-47.34	37	-2.99
1973-07	1974-04	-0.64	-5.74	9	-1.24

1975-08	1976-12	-1.18	-18.89	16	-2.10
1984-05	1985-08	-1.22	-18.28	15	-1.52
1987-12	1988-07	-0.49	-3.43	7	-1.56
1991-02	1991-11	-0.99	-8.93	9	-1.78
1992-01	1992-08	-1.07	-7.50	7	-1.33
1997-04	1998-01	-0.89	-7.99	9	-1.38
2001-12	2002-02	-0.84	-1.67	2	-1.27
2003-10	2004-10	-1.38	-16.53	12	-1.81
2010-11	2011-11	-1.03	-12.37	12	-1.88

Table 15: Malin Head. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Malin Head (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-03	1860-05	-1.17	-86.70	74	-2.41
1861-06	1861-09	-0.58	-1.73	3	-1.18
1868-07	1869-02	-0.71	-5.00	7	-1.24
1870-05	1871-07	-0.76	-10.65	14	-1.64
1874-08	1874-12	-0.78	-3.12	4	-1.18
1876-01	1876-03	-0.69	-1.38	2	-1.06
1880-08	1881-12	-0.65	-10.33	16	-1.51
1885-07	1886-12	-0.62	-10.49	17	-1.11
1887-06	1890-09	-0.99	-38.42	39	-2.37
1891-04	1892-09	-1.46	-24.77	17	-2.71
1893-06	1894-02	-0.49	-3.94	8	-1.32
1894-09	1896-02	-2.36	-40.20	17	-3.86
1899-12	1901-08	-1.57	-31.40	20	-3.44
1909-09	1910-02	-0.57	-2.83	5	-1.32
1911-01	1913-01	-2.27	-54.46	24	-4.70
1913-07	1914-02	-1.30	-9.11	7	-1.75
1919-09	1920-09	-0.92	-11.09	12	-1.73
1921-05	1922-06	-1.28	-16.59	13	-2.12
1923-02	1923-10	-1.17	-9.36	8	-1.72
1926-04	1926-10	-0.90	-5.43	6	-1.17
1932-06	1933-02	-0.55	-4.38	8	-1.25
1933-12	1934-09	-1.39	-12.53	9	-2.23
1938-02	1938-10	-0.77	-6.19	8	-1.10
1941-07	1942-08	-1.17	-15.19	13	-2.28
1944-08	1944-12	-0.73	-2.94	4	-1.33
1947-02	1947-05	-0.82	-2.46	3	-1.35
1953-01	1954-06	-1.25	-21.20	17	-1.87
1955-10	1956-12	-1.68	-23.59	14	-2.69
1959-06	1960-08	-1.11	-15.49	14	-2.25

1963-01	1965-01	-1.04	-25.08	24	-1.91
1969-03	1969-12	-1.03	-9.29	9	-1.47
1972-11	1974-01	-0.92	-12.92	14	-1.81
1975-08	1977-04	-1.02	-20.47	20	-1.79
1983-11	1985-07	-0.73	-14.68	20	-1.63
1986-09	1986-12	-0.65	-1.96	3	-1.18
1996-03	1998-01	-0.86	-18.90	22	-2.03
2001-10	2002-05	-1.05	-7.33	7	-1.65
2003-03	2004-09	-1.40	-25.15	18	-2.29

Table 16: Markree Castle. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Markree Castle (1850-2015)

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1853-12	1859-09	-1.49	-102.80	69	-2.35
1861-06	1861-09	-0.67	-2.02	3	-1.08
1863-11	1865-12	-2.13	-53.15	25	-4.33
1870-02	1871-07	-1.14	-19.45	17	-1.73
1871-12	1872-09	-0.93	-8.39	9	-1.32
1873-12	1874-12	-1.42	-17.07	12	-1.93
1875-12	1877-01	-1.01	-13.19	13	-1.84
1879-05	1879-09	-0.75	-2.98	4	-1.25
1879-11	1882-07	-0.92	-29.30	32	-2.14
1885-07	1886-12	-1.03	-17.43	17	-1.60
1887-10	1890-01	-0.82	-22.13	27	-1.85
1890-05	1894-05	-0.95	-45.46	48	-1.89
1895-02	1897-04	-1.13	-29.36	26	-2.22
1899-05	1900-08	-0.59	-8.82	15	-1.04
1902-10	1903-03	-0.99	-4.96	5	-1.29
1905-08	1907-06	-0.62	-13.66	22	-1.12
1909-08	1910-02	-0.95	-5.70	6	-1.76
1911-07	1912-03	-1.11	-8.85	8	-1.89
1921-06	1922-02	-0.85	-6.78	8	-1.20
1933-11	1934-12	-1.81	-23.53	13	-2.52
1938-02	1938-11	-1.03	-9.23	9	-1.72
1940-02	1940-05	-0.68	-2.03	3	-1.17
1941-07	1942-08	-1.26	-16.32	13	-1.94
1946-05	1947-04	-0.76	-8.34	11	-1.52
1952-08	1954-10	-1.60	-41.59	26	-3.17
1955-11	1958-08	-1.08	-35.71	33	-2.76
1959-08	1959-12	-1.00	-4.00	4	-1.57
1963-02	1965-01	-1.08	-24.94	23	-1.87

1969-10	1970-09	-0.71	-7.83	11	-1.26
1971-04	1973-02	-1.06	-23.29	22	-2.09
1973-06	1973-09	-0.76	-2.28	3	-1.00
1975-12	1977-11	-0.91	-20.97	23	-1.53
1979-03	1979-05	-0.97	-1.93	2	-1.23
1996-03	1996-11	-0.91	-7.27	8	-1.29
2001-12	2002-02	-0.82	-1.63	2	-1.03
2003-10	2004-04	-0.83	-4.99	6	-1.30
2006-07	2007-01	-0.75	-4.47	6	-1.22
2010-11	2011-10	-0.82	-9.02	11	-1.41

Table 17: Mullingar. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Mullingar (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-03	1860-06	-1.28	-95.95	75	-2.24
1863-07	1863-11	-0.60	-2.40	4	-1.17
1864-10	1865-08	-0.84	-8.36	10	-1.57
1868-07	1869-02	-0.97	-6.80	7	-1.51
1870-04	1871-07	-1.03	-15.43	15	-2.13
1874-07	1874-12	-1.02	-5.10	5	-1.30
1876-01	1876-03	-0.84	-1.67	2	-1.17
1880-06	1880-12	-0.98	-5.89	6	-1.55
1884-11	1890-06	-1.12	-75.30	67	-3.23
1891-01	1892-05	-1.07	-17.10	16	-1.98
1893-08	1894-11	-1.19	-17.85	15	-2.65
1895-04	1896-07	-0.84	-12.58	15	-2.01
1899-11	1900-08	-0.46	-4.18	9	-1.03
1902-09	1903-03	-0.96	-5.75	6	-1.29
1905-02	1910-02	-0.93	-55.97	60	-1.83
1911-08	1912-01	-0.74	-3.71	5	-1.52
1914-06	1914-12	-0.70	-4.17	6	-1.32
1919-10	1920-10	-0.79	-9.45	12	-1.78
1921-02	1923-10	-1.13	-36.02	32	-2.45
1926-05	1926-08	-0.60	-1.80	3	-1.10
1932-11	1933-03	-0.67	-2.69	4	-1.03
1933-09	1934-12	-1.76	-26.37	15	-2.64
1938-02	1938-11	-1.41	-12.72	9	-2.08
1939-10	1940-10	-0.57	-6.88	12	-1.10
1941-12	1942-09	-0.86	-7.74	9	-1.28

1944-06	1945-06	-0.79	-9.45	12	-1.65
1945-11	1946-09	-0.81	-8.09	10	-1.39
1949-09	1950-09	-0.68	-8.10	12	-1.14
1952-09	1954-05	-1.29	-25.84	20	-2.40
1956-01	1957-01	-1.16	-13.88	12	-1.93
1959-08	1960-02	-1.24	-7.46	6	-2.28
1963-09	1963-11	-0.77	-1.54	2	-1.06
1964-11	1964-12	-1.02	-1.02	1	-1.02
1969-10	1970-10	-1.39	-16.70	12	-2.01
1971-09	1974-12	-1.08	-42.00	39	-2.52
1975-08	1977-04	-1.24	-24.71	20	-2.26
1989-07	1990-02	-1.01	-7.05	7	-1.35
1992-04	1992-08	-0.78	-3.13	4	-1.03
1996-02	1996-08	-0.72	-4.29	6	-1.17
1997-04	1997-07	-0.60	-1.81	3	-1.08
2001-12	2002-02	-0.99	-1.97	2	-1.40
2003-11	2004-10	-1.38	-15.17	11	-1.69
2006-01	2006-12	-0.73	-8.05	11	-1.27

Table 18: Phoenix Park. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Phoenix Park (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-04	1860-06	-0.96	-70.72	74	-1.99
1863-07	1865-08	-0.67	-16.67	25	-1.57
1868-05	1868-12	-0.98	-6.87	7	-1.54
1870-05	1871-07	-1.07	-14.94	14	-1.89
1874-06	1875-01	-1.30	-9.08	7	-1.76
1880-09	1880-12	-0.61	-1.83	3	-1.18
1884-11	1885-10	-0.95	-10.48	11	-1.39
1887-07	1888-12	-1.43	-24.26	17	-2.83
1890-10	1892-03	-1.33	-22.53	17	-2.15
1893-09	1894-10	-1.15	-14.90	13	-2.03
1899-11	1900-06	-0.43	-3.03	7	-1.25
1902-01	1903-03	-0.58	-8.16	14	-1.26
1904-10	1910-02	-1.27	-81.33	64	-2.93
1911-06	1912-08	-1.17	-16.42	14	-2.09
1913-08	1915-01	-0.89	-15.10	17	-2.03
1919-10	1920-05	-0.64	-4.48	7	-1.10
1922-01	1923-11	-1.17	-25.77	22	-2.25
1926-05	1927-03	-0.63	-6.26	10	-1.18
1929-03	1930-01	-1.11	-11.05	10	-1.71
1933-09	1935-11	-1.47	-38.26	26	-3.29
1938-03	1939-02	-1.22	-13.45	11	-2.32

1942-03	1942-09	-1.07	-6.41	6	-1.41
1943-08	1945-06	-1.02	-22.52	22	-1.89
1945-11	1946-08	-1.12	-10.07	9	-1.88
1949-06	1950-09	-1.25	-18.71	15	-1.92
1953-10	1954-11	-1.07	-13.88	13	-1.73
1959-09	1960-02	-0.82	-4.11	5	-1.74
1962-01	1963-06	-0.71	-12.00	17	-1.18
1964-02	1965-01	-0.86	-9.45	11	-1.53
1970-06	1970-11	-0.82	-4.08	5	-1.17
1972-10	1973-09	-1.09	-12.04	11	-1.65
1975-07	1977-02	-1.12	-21.26	19	-1.74
1985-02	1985-06	-0.64	-2.57	4	-1.00
1989-01	1990-12	-1.07	-24.57	23	-2.14
1992-01	1993-05	-0.96	-15.29	16	-1.71
1995-09	1996-05	-0.62	-4.95	8	-1.15
1997-05	1997-06	-1.00	-1.00	1	-1.00
2001-12	2002-06	-0.69	-4.16	6	-1.46
2003-12	2005-06	-0.61	-10.91	18	-1.4
2006-01	2007-01	-0.99	-11.83	12	-1.57

Table 19: Portlaw. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Portlaw (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-1.36	-13.63	10	-1.68
1854-11	1856-02	-1.79	-26.90	15	-2.65
1856-08	1858-05	-0.94	-19.79	21	-1.76
1858-11	1859-11	-0.76	-9.12	12	-1.40
1863-07	1863-11	-0.61	-2.45	4	-1.09
1868-07	1868-11	-0.59	-2.36	4	-1.24
1869-12	1871-12	-1.19	-28.61	24	-2.19
1874-01	1875-09	-1.25	-25.07	20	-3.06
1878-11	1880-12	-1.34	-33.46	25	-2.41
1885-03	1885-08	-0.60	-2.98	5	-1.05
1887-09	1888-11	-1.80	-25.16	14	-2.88
1889-12	1891-12	-0.96	-22.98	24	-2.08
1893-09	1894-11	-0.99	-13.87	14	-1.83
1896-08	1897-04	-0.98	-7.82	8	-1.58
1902-01	1902-07	-0.53	-3.17	6	-1.09
1905-02	1908-03	-1.29	-47.83	37	-2.47
1909-09	1910-08	-0.75	-8.20	11	-1.12
1911-08	1911-12	-1.27	-5.06	4	-1.65
1917-11	1918-12	-0.68	-8.87	13	-1.63
1920-02	1920-07	-0.73	-3.64	5	-1.13
1921-10	1923-10	-0.83	-19.88	24	-1.84

1925-12	1927-12	-0.58	-14.03	24	-1.53
1932-11	1933-02	-0.54	-1.62	3	-1.11
1933-12	1934-12	-1.29	-15.44	12	-1.85
1938-03	1938-11	-0.71	-5.70	8	-1.68
1942-02	1942-09	-0.70	-4.92	7	-1.50
1942-11	1943-10	-0.88	-9.73	11	-1.24
1944-05	1945-06	-1.04	-13.52	13	-1.73
1949-12	1951-01	-0.79	-10.32	13	-1.71
1953-01	1955-01	-1.01	-24.22	24	-2.04
1956-04	1956-09	-1.12	-5.59	5	-1.77
1959-09	1960-08	-1.05	-11.51	11	-1.80
1963-09	1963-11	-0.76	-1.52	2	-1.05
1968-08	1968-12	-1.09	-4.34	4	-1.29
1969-12	1972-05	-1.06	-30.60	29	-1.73
1973-05	1974-01	-0.92	-7.39	8	-1.32
1975-05	1977-02	-1.47	-30.79	21	-2.10
1984-09	1984-11	-1.04	-2.07	2	-1.10
1989-08	1990-02	-0.96	-5.74	6	-1.57
1991-02	1993-05	-0.67	-18.16	27	-1.41
1997-03	1997-08	-1.31	-6.57	5	-1.73
2000-01	2000-12	-0.93	-10.22	11	-1.54
2003-12	2004-10	-1.14	-11.38	10	-2.10
2008-02	2008-10	-0.73	-5.86	8	-1.05
2011-01	2012-08	-1.47	-27.90	19	-2.36
2013-09	2014-02	-0.84	-4.18	5	-1.08
2015-02	2015-12	-1.51	-15.08	10	-2.22

Table 20: Rathdrum. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Rathdrum (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-0.81	-8.05	10	-1.27
1854-10	1860-06	-0.92	-62.87	68	-2.46
1864-10	1865-08	-0.66	-6.62	10	-1.43
1868-07	1868-12	-0.70	-3.48	5	-1.08
1870-05	1871-07	-0.85	-11.94	14	-1.62
1873-12	1875-10	-1.88	-41.36	22	-2.77
1880-06	1880-11	-0.98	-4.89	5	-1.33
1885-02	1885-10	-0.93	-7.43	8	-1.60
1887-10	1888-07	-1.52	-13.70	9	-2.16
1890-10	1891-10	-0.81	-9.68	12	-1.38
1893-06	1894-10	-1.82	-29.07	16	-3.49
1895-10	1896-10	-1.06	-12.75	12	-1.42
1904-12	1905-11	-1.19	-13.11	11	-1.87
1906-08	1908-03	-1.45	-27.62	19	-2.66
1909-09	1910-02	-0.58	-2.92	5	-1.05
1914-05	1915-01	-0.92	-7.32	8	-1.52
1919-10	1920-07	-0.86	-7.70	9	-1.28

1921-10	1923-10	-0.85	-20.41	24	-1.59
1925-12	1928-01	-0.80	-20.09	25	-2.04
1933-12	1934-12	-1.08	-12.97	12	-1.69
1938-03	1938-12	-1.73	-15.59	9	-2.65
1944-01	1945-03	-1.24	-17.42	14	-1.86
1945-11	1946-08	-0.74	-6.68	9	-1.36
1949-05	1950-09	-1.00	-16.07	16	-1.68
1953-01	1954-11	-1.10	-24.13	22	-2.16
1956-05	1956-09	-1.07	-4.26	4	-1.60
1959-09	1960-02	-0.93	-4.63	5	-1.96
1961-11	1963-04	-0.78	-13.30	17	-1.32
1968-10	1968-12	-0.86	-1.72	2	-1.23
1970-03	1972-05	-1.15	-29.82	26	-2.09
1973-03	1974-01	-1.08	-10.81	10	-1.70
1975-05	1977-02	-1.72	-36.17	21	-2.37
1978-10	1978-12	-1.06	-2.12	2	-1.09
1987-08	1987-10	-0.80	-1.59	2	-1.05
1989-01	1990-02	-1.31	-17.00	13	-2.19
1990-04	1993-06	-1.16	-44.21	38	-2.08
1997-03	1997-11	-0.66	-5.26	8	-1.42
2000-09	2000-11	-1.12	-2.24	2	-1.24
2001-12	2002-05	-0.81	-4.05	5	-1.25
2005-09	2006-09	-0.43	-5.19	12	-1.06
2007-12	2008-09	-1.03	-9.28	9	-1.50
2011-08	2012-07	-0.81	-8.91	11	-1.00
2015-02	2015-12	-1.39	-13.93	10	-2.07

Table 22: Roches Point. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Roches Point (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-01	1852-11	-0.79	-7.94	10	-1.29
1854-10	1860-06	-0.88	-59.70	68	-2.75
1864-10	1865-08	-0.74	-7.38	10	-1.02
1870-09	1871-07	-0.65	-6.47	10	-1.17
1874-07	1875-01	-1.19	-7.15	6	-1.61
1880-09	1880-11	-0.85	-1.70	2	-1.04
1887-09	1888-12	-1.25	-18.70	15	-2.24
1891-03	1891-10	-0.96	-6.74	7	-1.32
1894-02	1894-11	-0.92	-8.29	9	-1.29
1896-08	1897-04	-0.94	-7.54	8	-1.40
1902-09	1903-07	-0.82	-8.20	10	-1.79
1905-02	1908-01	-1.58	-55.25	35	-2.93
1908-12	1910-11	-1.11	-25.57	23	-1.92
1911-08	1912-01	-0.78	-3.91	5	-1.41
1914-11	1914-12	-1.29	-1.29	1	-1.29

1917-11	1919-01	-0.71	-9.88	14	-1.58
1919-09	1920-07	-1.43	-14.33	10	-1.90
1921-07	1924-01	-0.80	-24.11	30	-2.08
1926-10	1927-12	-1.42	-19.81	14	-2.14
1933-12	1936-01	-1.15	-28.69	25	-2.76
1938-04	1938-12	-0.71	-5.67	8	-1.34
1942-02	1943-11	-0.97	-20.31	21	-1.88
1944-03	1944-12	-1.07	-9.63	9	-1.54
1949-12	1950-09	-0.72	-6.49	9	-1.36
1952-09	1954-06	-1.38	-28.97	21	-2.43
1955-12	1957-02	-0.83	-11.62	14	-1.98
1959-09	1960-07	-0.54	-5.39	10	-1.83
1962-01	1964-05	-0.84	-23.51	28	-1.99
1967-06	1969-01	-0.82	-15.64	19	-1.48
1970-01	1972-03	-1.36	-35.32	26	-2.52
1972-09	1974-01	-1.01	-16.09	16	-1.66
1975-05	1977-01	-1.64	-32.88	20	-2.56
1985-01	1985-08	-0.67	-4.66	7	-1.26
1989-10	1989-12	-1.11	-2.22	2	-1.22
1990-12	1991-11	-0.83	-9.09	11	-1.73
1992-03	1993-05	-0.82	-11.43	14	-1.40
2000-08	2001-01	-0.73	-3.66	5	-1.52
2003-12	2004-10	-1.09	-10.85	10	-1.83
2006-07	2006-12	-0.72	-3.59	5	-1.01
2010-11	2013-03	-1.75	-49.01	28	-2.60
2013-08	2014-02	-0.98	-5.87	6	-1.34
2015-02	2015-12	-1.26	-12.58	10	-2.26

Table 23: Shannon Airport. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Shannon Airport (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-03	1860-05	-1.19	-87.86	74	-2.41
1861-06	1861-07	-1.05	-1.05	1	-1.05
1863-07	1863-11	-0.79	-3.14	4	-1.33
1864-10	1865-05	-1.05	-7.37	7	-1.79
1868-07	1868-12	-0.63	-3.15	5	-1.09
1880-02	1882-03	-1.29	-32.20	25	-2.31
1884-10	1886-12	-1.08	-27.96	26	-2.26
1887-07	1890-11	-1.06	-42.49	40	-2.82
1891-02	1892-02	-1.20	-14.45	12	-1.80
1893-08	1894-05	-1.17	-10.53	9	-1.85
1895-05	1896-09	-1.24	-19.81	16	-1.82
1902-04	1903-07	-1.11	-16.66	15	-2.33

1905-01	1906-10	-1.34	-28.24	21	-2.21
1907-03	1907-11	-0.74	-5.89	8	-1.21
1909-09	1910-02	-0.88	-4.38	5	-1.57
1911-05	1912-06	-1.05	-13.60	13	-2.45
1917-12	1918-07	-0.78	-5.47	7	-1.36
1919-10	1920-05	-1.00	-6.98	7	-1.52
1921-06	1923-05	-0.60	-13.71	23	-1.08
1932-06	1935-02	-1.31	-41.95	32	-3.06
1938-04	1938-08	-0.69	-2.77	4	-1.29
1940-01	1943-11	-0.69	-31.96	46	-1.40
1944-06	1944-11	-0.76	-3.78	5	-1.22
1949-09	1949-11	-0.64	-1.29	2	-1.15
1952-12	1954-03	-1.94	-29.11	15	-3.39
1955-10	1956-12	-0.97	-13.59	14	-1.97
1959-08	1959-12	-1.62	-6.48	4	-2.19
1963-01	1964-12	-0.98	-22.54	23	-2.00
1967-06	1969-01	-0.73	-13.92	19	-1.28
1970-01	1970-10	-0.84	-7.60	9	-1.83
1971-07	1973-09	-1.08	-28.21	26	-2.02
1975-09	1977-08	-0.87	-19.95	23	-1.50
1985-01	1985-08	-1.40	-9.82	7	-2.24
1987-08	1988-03	-0.66	-4.60	7	-1.54
1989-09	1990-02	-0.81	-4.07	5	-1.08
1992-06	1993-06	-0.47	-5.64	12	-1.15
1996-07	1997-08	-0.76	-9.88	13	-1.55
2001-12	2002-02	-0.89	-1.79	2	-1.20
2003-05	2004-10	-1.20	-20.44	17	-1.88
2006-06	2006-12	-0.98	-5.90	6	-1.47

Table 24: Strokestown. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Strokestown (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-01	1860-05	-1.34	-102.01	76	-2.75
1861-06	1861-09	-0.55	-1.65	3	-1.25
1864-10	1865-08	-0.67	-6.66	10	-1.31
1868-07	1869-01	-0.86	-5.19	6	-1.40
1870-04	1871-07	-0.94	-14.16	15	-2.01
1874-07	1874-12	-1.07	-5.35	5	-1.38
1880-08	1881-12	-0.71	-11.33	16	-1.68
1885-03	1886-12	-0.67	-14.05	21	-1.16
1887-07	1892-07	-0.94	-56.28	60	-2.79

1893-08	1894-06	-1.23	-12.27	10	-2.16
1895-02	1896-09	-1.06	-20.07	19	-1.86
1902-10	1903-03	-0.84	-4.22	5	-1.25
1905-02	1908-01	-0.88	-30.86	35	-1.68
1909-09	1910-08	-0.81	-8.91	11	-1.74
1911-02	1912-03	-1.46	-19.02	13	-2.72
1915-05	1916-05	-0.83	-9.94	12	-1.06
1918-08	1920-10	-0.83	-21.66	26	-2.06
1921-02	1923-10	-1.53	-49.12	32	-3.57
1929-11	1930-01	-0.59	-1.18	2	-1.05
1932-08	1933-03	-0.97	-6.79	7	-1.54
1933-10	1934-12	-1.92	-26.95	14	-3.19
1938-02	1938-11	-1.20	-10.81	9	-2.00
1941-05	1942-08	-0.93	-14.02	15	-1.71
1944-08	1944-11	-0.74	-2.22	3	-1.01
1952-08	1954-03	-2.01	-38.21	19	-3.19
1956-02	1956-12	-1.16	-11.60	10	-2.59
1959-07	1960-02	-1.28	-8.95	7	-2.58
1963-01	1963-11	-1.02	-10.19	10	-1.45
1969-10	1970-09	-0.87	-9.61	11	-1.60
1971-09	1974-02	-1.15	-33.45	29	-2.21
1975-08	1977-02	-0.96	-17.20	18	-1.73
1979-02	1979-08	-0.66	-3.96	6	-1.48
1984-06	1985-08	-1.01	-14.09	14	-2.02
1992-03	1992-08	-0.99	-4.93	5	-1.22
2001-11	2002-02	-1.18	-3.54	3	-1.65
2004-05	2004-10	-0.86	-4.30	5	-1.24
2006-01	2006-10	-0.53	-4.79	9	-1.13

Table 25: UC Galway. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at UC Galway (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1854-01	1860-05	-1.17	-88.66	76	-2.22
1867-12	1869-09	-0.87	-18.25	21	-1.67
1870-09	1871-04	-0.44	-3.10	7	-1.50
1871-10	1872-11	-1.65	-21.47	13	-2.25
1875-10	1876-09	-1.12	-12.29	11	-2.24
1880-09	1880-12	-0.83	-2.50	3	-1.35
1881-07	1881-12	-0.54	-2.72	5	-1.28
1885-02	1886-06	-0.99	-15.87	16	-1.85
1887-06	1888-06	-0.76	-9.06	12	-1.33

1888-09	1892-05	-1.10	-48.50	44	-2.45
1893-09	1894-03	-1.04	-6.25	6	-1.72
1895-04	1896-07	-1.44	-21.62	15	-2.49
1900-04	1900-08	-0.70	-2.80	4	-1.10
1902-09	1903-07	-1.09	-10.91	10	-1.92
1905-02	1906-12	-1.18	-25.97	22	-2.49
1907-01	1907-12	-0.87	-9.53	11	-1.33
1908-10	1910-06	-1.73	-34.53	20	-3.19
1911-07	1912-03	-1.13	-9.00	8	-1.81
1915-12	1916-12	-1.59	-19.13	12	-2.50
1917-05	1917-09	-0.67	-2.66	4	-1.00
1917-12	1920-05	-1.06	-30.63	29	-1.99
1921-06	1922-04	-1.00	-10.03	10	-1.57
1923-05	1923-11	-0.92	-5.53	6	-1.60
1932-06	1934-10	-1.08	-30.34	28	-2.18
1936-02	1936-07	-1.02	-5.12	5	-1.20
1939-12	1943-11	-0.85	-40.14	47	-1.78
1947-02	1947-05	-0.63	-1.88	3	-1.20
1951-07	1951-12	-0.76	-3.82	5	-1.24
1953-01	1954-03	-1.12	-15.66	14	-2.09
1955-11	1957-01	-1.22	-17.06	14	-2.48
1959-08	1959-12	-1.40	-5.61	4	-1.98
1962-10	1964-12	-1.12	-29.17	26	-2.31
1967-06	1967-10	-0.72	-2.89	4	-1.20
1970-01	1970-09	-0.50	-4.00	8	-1.30
1971-08	1973-10	-1.35	-34.98	26	-2.08
1976-09	1977-04	-0.70	-4.87	7	-1.14
1978-11	1979-05	-0.76	-4.55	6	-1.07
1985-02	1985-05	-0.73	-2.19	3	-1.02
1987-12	1988-03	-0.44	-1.31	3	-1.08
1993-11	1994-01	-0.66	-1.32	2	-1.18
1996-01	1998-01	-1.36	-32.55	24	-2.20
2001-12	2002-02	-1.06	-2.11	2	-1.46
2004-05	2004-10	-1.21	-6.05	5	-1.69
2006-08	2006-11	-0.36	-1.08	3	-1.01
2010-12	2011-10	-0.73	-7.27	10	-1.23

Table 26: Valentia. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Valentia (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1851-12	1852-11	-1.35	-14.87	11	-1.92
1854-10	1860-01	-1.27	-80.20	63	-3.99
1864-12	1865-10	-0.69	-6.92	10	-1.12
1870-09	1871-07	-0.59	-5.92	10	-1.26
1880-06	1881-12	-0.82	-14.77	18	-1.53
1887-08	1889-10	-1.11	-28.94	26	-2.45

1891-05	1891-10	-1.21	-6.04	5	-1.68
1893-08	1894-11	-1.20	-18.06	15	-2.45
1895-11	1897-05	-1.17	-21.06	18	-1.99
1902-01	1903-03	-0.76	-10.61	14	-1.48
1906-04	1912-01	-1.05	-72.38	69	-2.10
1918-08	1918-12	-0.53	-2.11	4	-1.01
1919-10	1920-10	-0.99	-11.83	12	-1.72
1921-10	1923-10	-0.65	-15.50	24	-1.51
1927-01	1928-04	-1.00	-14.97	15	-1.69
1931-10	1935-02	-1.40	-56.07	40	-3.67
1936-10	1937-03	-0.91	-4.56	5	-1.47
1940-07	1943-11	-0.84	-33.64	40	-1.97
1944-05	1945-06	-1.15	-15.00	13	-2.06
1952-09	1954-02	-1.71	-29.15	17	-2.83
1955-10	1957-09	-1.21	-27.94	23	-2.60
1959-08	1959-12	-1.26	-5.05	4	-1.95
1962-02	1963-11	-0.96	-20.13	21	-1.96
1967-02	1968-12	-0.96	-21.06	22	-2.02
1969-11	1972-12	-1.19	-44.06	37	-2.66
1973-06	1974-02	-0.79	-6.32	8	-1.17
1975-07	1976-12	-1.27	-21.53	17	-2.22
1987-08	1987-10	-0.63	-1.26	2	-1.18
1991-02	1991-09	-0.42	-2.94	7	-1.11
1993-08	1993-12	-0.80	-3.18	4	-1.19
1997-10	1998-01	-0.77	-2.31	3	-1.35
2001-12	2002-05	-0.49	-2.44	5	-1.04
2004-06	2004-10	-0.95	-3.80	4	-1.36
2004-11	2005-11	-0.79	-9.50	12	-1.67

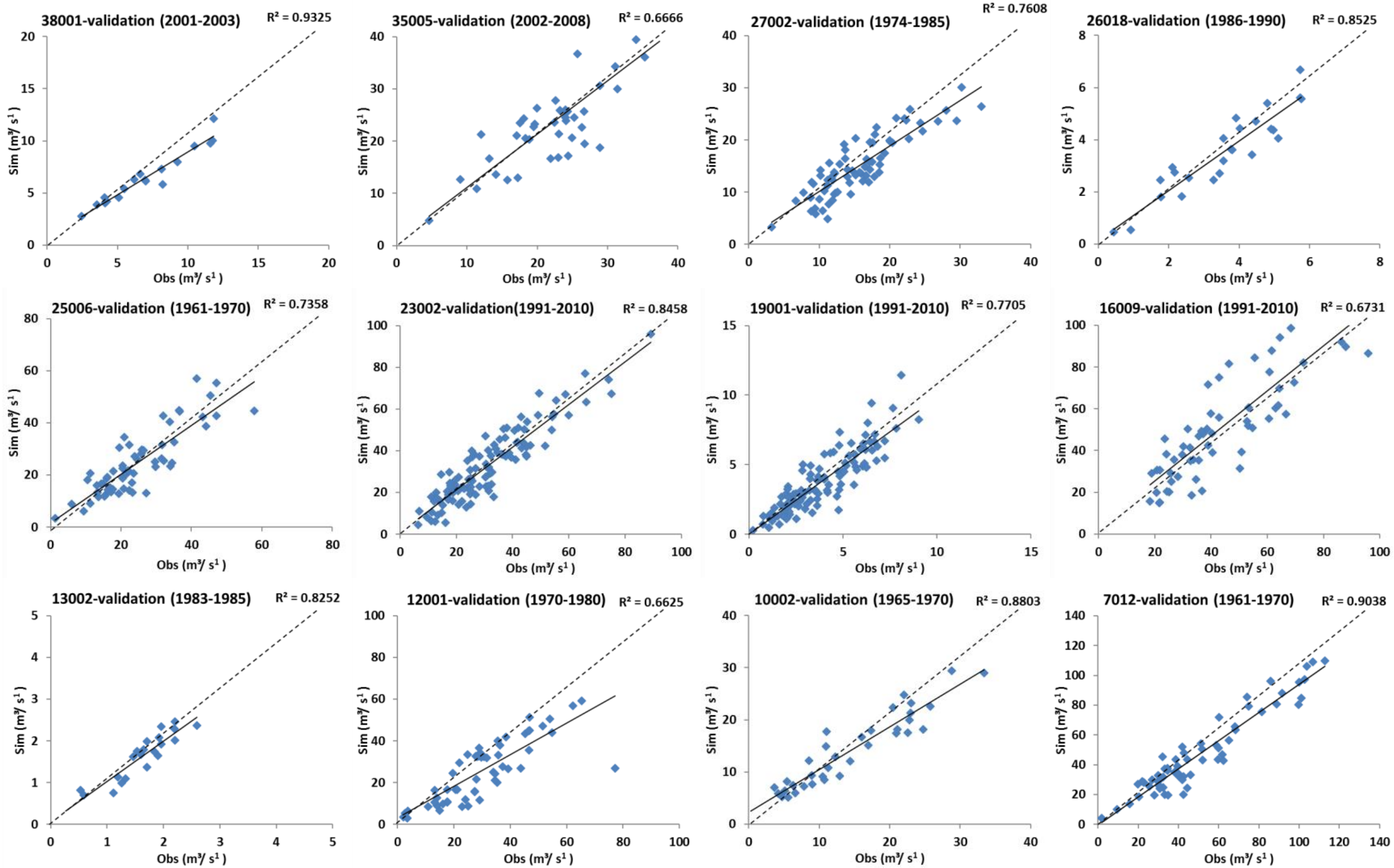
Table 27: Waterford. Drought start and termination dates together with the duration, mean SPI-12, accumulated deficit and maximum intensity (min. SPI-12) for each event identified at Waterford (1850-2015).

Drought Start	Drought termination	Mean SPI-12	Accumulated Deficit	Drought Duration	Maximum Intensity
1852-04	1852-06	-0.79	-1.57	2	-1.01
1854-10	1856-02	-2.00	-32.06	16	-2.94
1857-09	1860-06	-1.12	-37.01	33	-1.66
1863-08	1865-08	-1.34	-32.24	24	-2.68
1874-07	1875-01	-0.89	-5.34	6	-1.31
1887-09	1888-07	-1.77	-17.74	10	-2.45
1891-03	1891-12	-0.86	-7.76	9	-1.50
1892-10	1895-03	-1.93	-55.86	29	-3.44
1905-10	1910-02	-1.15	-59.77	52	-2.79

1913-08	1920-10	-1.09	-93.72	86	-2.28
1922-11	1923-04	-0.65	-3.23	5	-1.16
1924-04	1924-09	-0.51	-2.57	5	-1.12
1927-01	1927-09	-0.96	-7.65	8	-1.54
1932-11	1936-02	-0.86	-33.59	39	-2.30
1938-03	1938-12	-0.90	-8.13	9	-1.34
1941-12	1945-06	-0.84	-35.13	42	-1.66
1949-12	1950-09	-0.60	-5.40	9	-1.25
1953-01	1955-01	-1.01	-24.32	24	-2.43
1956-05	1957-03	-0.65	-6.49	10	-1.98
1959-09	1960-07	-0.55	-5.49	10	-1.40
1969-12	1972-05	-1.13	-32.68	29	-1.69
1973-06	1974-01	-0.67	-4.71	7	-1.13
1975-05	1977-02	-1.42	-29.84	21	-2.06
1984-06	1985-06	-0.83	-9.91	12	-1.38
1989-08	1990-02	-1.00	-5.97	6	-1.44
1991-02	1993-05	-0.87	-23.37	27	-1.70
2004-06	2006-09	-0.57	-15.41	27	-1.94
2015-04	2015-12	-0.77	-6.19	8	-1.25

Appendix 3 winter half year validation results from chapter 5

Winter half year (Oct, Nov, Dec, Jan, Feb and Mar) simulated and observed flow validation correlation results at each study catchment



Appendix 4 Supplementary drought information for chapter 5

The tables show the reconstructed river flow 1850-2105 results top ten ranked Drought Severity Index (DSI) results based on drought duration. The Drought Severity Index (DSI) was applied to the reconstructed flows to calculate the runoff deficiencies relative to the baseline 1961-1990 a drought start is defined when the anomaly becomes negative and ends when the anomaly returns to a positive value. Table shows the drought start and end dates together with the duration in months, mean low-flow deficit (*m^3/s^1*) and accumulated deficit (*m^3/s^1*).

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
38001 Northwest BFI (0.28)	1	1856-02	1856-12	-2.13	-21.28	10
	2	1888-01	1888-11	-1.57	-15.68	10
	3	1933-03	1934-01	-3.11	-31.08	10
	4	1854-02	1854-11	-2.27	-20.44	9
	5	1855-01	1855-10	-2.74	-24.67	9
	6	1873-11	1874-08	-2.01	-18.06	9
	7	1902-02	1902-11	-3.08	-27.71	9
	8	1922-03	1922-12	-1.94	-17.50	9
	9	2003-02	2003-11	-2.40	-21.56	9
	10	1850-03	1850-11	-1.54	-12.34	8

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
35005 West BFI (0.61)	1	1855-01	1855-12	-6.58	-72.39	11
	2	1864-02	1865-01	-9.58	-105.37	11
	3	1856-03	1857-01	-8.13	-81.32	10
	4	1858-02	1858-12	-6.22	-62.16	10
	5	1871-04	1872-01	-5.08	-45.71	9
	6	1888-02	1888-11	-4.88	-43.91	9
	7	1895-02	1895-11	-7.44	-66.93	9
	8	1933-04	1934-01	-8.33	-74.93	9
	9	1937-04	1938-01	-6.65	-59.85	9
	10	1947-02	1947-11	-6.26	-56.37	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
27002 West BFI (0.70)	1	1855-01	1856-01	-4.43	-53.14	12
	2	1888-01	1888-11	-4.53	-45.26	10
	3	1993-02	1993-12	-3.33	-33.33	10
	4	1856-03	1856-12	-5.56	-50.04	9
	5	1881-01	1881-10	-4.88	-43.96	9
	6	1887-03	1887-12	-5.99	-53.87	9
	7	1889-03	1889-12	-4.57	-41.14	9
	8	1893-03	1893-12	-5.40	-48.59	9
	9	1895-02	1895-11	-5.65	-50.87	9
	10	1933-04	1934-01	-6.40	-57.64	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
26018 West BFI (0.72)	1	1855-02	1856-01	-1.15	-12.66	11
	2	1921-02	1922-01	-1.49	-16.42	11
	3	1858-02	1858-12	-0.90	-9.02	10
	4	1856-03	1856-12	-1.27	-11.46	9
	5	1887-03	1887-12	-1.50	-13.54	9
	6	1888-02	1888-11	-0.90	-8.10	9
	7	1893-03	1893-12	-1.40	-12.60	9
	8	1895-02	1895-11	-1.22	-10.95	9
	9	1919-03	1919-12	-1.41	-12.68	9
	10	1933-04	1934-01	-1.46	-13.15	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
25006 Midlands BFI (0.71)	1	1887-03	1888-12	-7.60	-159.67	21
	2	1975-03	1976-10	-7.93	-150.68	19
	3	1850-01	1850-12	-8.30	-91.32	11
	4	2003-03	2004-01	-8.77	-87.70	10
	5	1854-03	1854-12	-7.25	-65.29	9
	6	1855-04	1856-01	-8.75	-78.77	9
	7	1864-02	1864-11	-8.63	-77.66	9
	8	1889-03	1889-12	-8.29	-74.63	9
	9	1932-03	1932-12	-8.43	-75.86	9
	10	1933-04	1934-01	-9.19	-82.67	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
23002 Southwest BFI (0.31)	1	1933-02	1934-01	-9.83	-108.16	11
	2	1919-02	1919-12	-10.15	-101.47	10
	3	1963-12	1964-10	-5.02	-50.20	10
	4	2003-01	2003-11	-9.11	-91.13	10
	5	1854-02	1854-11	-8.02	-72.15	9
	6	1855-01	1855-10	-10.39	-93.54	9
	7	1856-03	1856-12	-9.40	-84.57	9
	8	1887-02	1887-11	-11.76	-105.88	9
	9	1955-02	1955-11	-8.13	-73.17	9
	10	1969-02	1969-11	-11.13	-100.21	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
	1	1906-03	1907-11	-1.55	-31.04	20
	2	1854-02	1855-03	-1.67	-21.73	13
	3	1917-02	1918-01	-1.06	-11.69	11
	4	1991-12	1992-11	-1.02	-11.27	11
19001 South BFI (0.68)	5	1887-02	1887-12	-1.80	-18.03	10
	6	1896-02	1896-12	-1.43	-14.35	10
	7	1908-02	1908-12	-1.37	-13.66	10
	8	1911-01	1911-11	-1.51	-15.14	10
	9	1932-02	1932-12	-1.34	-13.38	10
	10	1933-03	1934-01	-1.49	-14.94	10

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
	1	1854-03	1855-12	-15.50	-325.40	21
	2	1850-01	1850-12	-17.33	-190.65	11
	3	1991-12	1992-11	-9.27	-101.99	11
	4	1851-03	1852-01	-16.19	-161.91	10
16009 South BFI (0.63)	5	1969-03	1970-01	-17.08	-170.79	10
	6	1971-03	1972-01	-13.93	-139.33	10
	7	1856-03	1856-12	-12.88	-115.93	9
	8	1857-02	1857-11	-11.35	-102.11	9
	9	1864-02	1864-11	-16.55	-148.97	9
	10	1887-03	1887-12	-19.91	-179.19	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
	1	1854-03	1855-12	-0.55	-11.63	21
	2	1906-03	1907-11	-0.53	-10.55	20
	3	1975-03	1976-11	-0.70	-13.93	20
	4	1971-02	1972-01	-0.58	-6.42	11
13002 Southeast BFI (0.73)	5	1991-12	1992-11	-0.51	-5.60	11
	6	1887-03	1888-01	-0.71	-7.07	10
	7	1893-03	1894-01	-0.66	-6.56	10
	8	1953-01	1953-11	-0.51	-5.07	10
	9	1851-04	1852-01	-0.53	-4.76	9
	10	1856-03	1856-12	-0.39	-3.48	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
12001 Southeast BFI (0.72)	1	1854-02	1855-12	-11.16	-245.49	22
	2	1906-03	1907-10	-13.58	-258.11	19
	3	1887-02	1888-01	-11.92	-131.07	11
	4	1917-02	1918-01	-7.13	-78.43	11
	5	2014-12	2015-11	-13.83	-152.09	11
	6	1878-03	1879-01	-7.01	-70.12	10
	7	1893-03	1894-01	-14.85	-148.46	10
	8	1932-02	1932-12	-9.84	-98.43	10
	9	1935-01	1935-11	-8.57	-85.71	10
	10	1941-03	1942-01	-12.65	-126.50	10

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
10002 East BFI (0.54)	1	1991-12	1992-11	-3.76	-41.40	11
	2	1948-02	1948-12	-2.64	-26.36	10
	3	1854-02	1854-11	-4.68	-42.09	9
	4	1887-02	1887-11	-5.35	-48.17	9
	5	1891-01	1891-10	-3.11	-27.96	9
	6	1893-03	1893-12	-6.83	-61.49	9
	7	1949-01	1949-10	-4.97	-44.69	9
	8	1953-01	1953-10	-4.85	-43.69	9
	9	1973-02	1973-11	-4.01	-36.06	9
	10	1978-03	1978-12	-5.72	-51.46	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean DSI m^3/s^1 deficit*	*Accumulated DSI m^3/s^1 Deficit*	*Drought duration months*
7012 East BFI (0.68)	1	1890-02	1891-12	-20.30	-446.50	22
	2	1855-01	1856-01	-16.27	-195.28	12
	3	1906-03	1907-03	-17.92	-215.04	12
	4	2005-03	2006-03	-14.73	-176.76	12
	5	1857-05	1858-04	-17.10	-188.12	11
	6	1887-03	1888-01	-22.72	-227.16	10
	7	1893-03	1894-01	-24.72	-247.16	10
	8	1934-02	1934-12	-21.24	-212.40	10
	9	1969-03	1970-01	-18.70	-187.00	10
	10	1971-03	1972-01	-23.38	-233.83	10

Appendix 5 Supplementary drought information for chapter 5

Appendix 5 presents the ten longest 12 month running mean DSI deficits at the twelve study catchments 1850-2015. The drought deficits are calculated as a 12 month running mean anomaly to a baseline of 1961-1990 a drought start is defined when the anomaly becomes negative and ends when the anomaly returns to a positive value.

	Drought Start	Drought ends	Drought Duration (months)
38001 Northwest BFI (0.28)	1853-12	1860-06	78
	1929-01	1934-12	71
	1899-11	1903-08	45
	1971-03	1974-08	41
	1913-08	1916-09	37
	1891-01	1894-01	36
	1887-01	1889-12	35
	1904-08	1906-11	27
	1911-01	1913-01	24
	1894-10	1896-09	23

	Drought Start	Drought ends	Drought Duration (months)
35005 West BFI (0.61)	1884-08	1894-08	120
	1853-12	1859-11	71
	1945-11	1950-09	58
	1955-10	1960-01	51
	1933-05	1937-03	46
	1873-11	1877-08	45
	1879-01	1882-08	43
	1904-10	1908-03	41
	1970-12	1974-01	37
	1870-01	1872-10	33

	Drought Start	Drought ends	Drought Duration (months)
27002 West BFI (0.70)	1854-01	1860-07	78
	1887-05	1892-09	64
	1940-01	1944-11	58
	1932-02	1935-05	39
	1904-12	1907-12	36
	1962-02	1965-01	35
	1971-02	1974-01	35
	1975-09	1978-03	30
	1879-11	1882-04	29
	1895-02	1897-05	27

	Drought Start	Drought ends	Drought Duration (months)
26018 West BFI (0.72)	1853-12	1860-07	79
	1887-04	1892-09	65
	1918-08	1923-11	63
	1904-12	1908-03	39
	1962-01	1965-01	36
	1971-03	1974-03	36
	1870-01	1872-09	32
	1932-07	1935-03	32
	1952-03	1954-09	30
	1908-05	1910-10	29

	Drought Start	Drought ends	Drought Duration (months)
25006 Midlands BFI (0.71)	1969-11	1974-02	51
	1887-10	1890-11	37
	1854-04	1857-01	33
	1857-09	1860-06	33
	1905-02	1907-11	33
	1863-10	1866-03	29
	1975-09	1978-01	28
	1932-11	1935-02	27
	1884-11	1886-12	25
	1963-01	1965-01	24

	Drought Start	Drought ends	Drought Duration (months)
23002 Southwest BFI (0.31)	1853-12	1860-06	78
	1940-11	1944-11	48
	1887-03	1890-11	44
	1932-02	1935-04	38
	1962-02	1964-12	34
	1971-02	1973-10	32
	1879-10	1882-03	29
	1884-08	1886-12	28
	1975-08	1977-11	27
	2003-02	2005-04	26

	Drought Start	Drought ends	Drought Duration (months)
19001 South BFI (0.68)	1906-03	1912-07	76
	1941-02	1946-11	69
	1969-11	1974-01	50
	1932-03	1936-02	47
	1854-01	1857-11	46
	1990-04	1993-10	42
	2003-11	2007-01	38
	1889-08	1892-08	36
	1952-09	1955-07	34
	1921-04	1923-11	31

	Drought Start	Drought ends	Drought Duration (months)
16009 South BFI (0.63)	1854-01	1860-09	80
	1969-11	1974-09	58
	1942-01	1946-08	55
	1989-08	1993-10	50
	1951-08	1954-11	39
	2003-11	2007-02	39
	1905-02	1908-03	37
	1893-02	1896-02	36
	1863-05	1866-01	32
	1921-05	1923-12	31

	Drought Start	Drought ends	Drought Duration (months)
13002 Southeast BFI (0.73)	1854-09	1860-07	70
	1887-09	1892-01	52
	1969-12	1974-04	52
	1989-08	1993-09	49
	1905-02	1908-03	37
	1921-10	1924-01	27
	1952-09	1954-12	27
	1975-01	1977-04	27
	1864-01	1865-12	23
	1884-11	1886-10	23

	Drought Start	Drought ends	Drought Duration (months)
12001 Southeast BFI (0.72)	1887-03	1895-12	105
	1904-10	1912-01	87
	1854-03	1860-09	78
	1941-01	1946-11	70
	1932-05	1937-03	58
	1919-10	1924-01	51
	1969-11	1974-02	51
	1990-04	1993-08	40
	2003-11	2006-10	35
	1914-01	1916-11	34

	Drought Start	Drought ends	Drought Duration (months)
10002 East BFI (0.54)	1854-03	1860-06	75
	1990-03	1993-09	42
	1969-11	1972-07	32
	1921-05	1923-10	29
	1925-09	1928-01	28
	1943-04	1945-07	27
	1906-08	1908-09	25
	1975-01	1977-02	25
	1873-11	1875-11	24
	1952-11	1954-11	24

	Drought Start	Drought ends	Drought Duration (months)
7012 East BFI (0.68)	1887-04	1897-02	118
	1969-11	1977-03	88
	1853-12	1860-09	81
	1904-11	1908-02	39
	1962-01	1965-01	36
	1863-05	1866-03	34
	1869-12	1872-10	34
	1952-04	1954-10	30
	1933-10	1936-01	27
	2010-11	2013-01	26

Appendix 6 Supplementary drought information for chapter 5

Top ten ranked Q95 drought results based on duration. The drought deficits are calculated as Q95 across all months, a drought start period is defined when the Q95 value becomes negative and ends when the Q95 value returns to a positive value. Table shows the drought period start and end dates together with the duration in months, mean low-flow deficit (*m^3/s^1*) and accumulated deficit (*m^3/s^1*).

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m^3/s^1 deficit*	*Accumulated Q95 m^3/s^1 Deficit*	*Drought duration months*
38001 Northwest BFI (0.28)	1	1953-01	1953-06	-0.20	-0.99	5
	2	1929-03	1929-07	-0.42	-1.66	4
	3	1933-09	1934-01	-1.00	-3.99	4
	4	1975-06	1975-10	-0.23	-0.94	4
	5	1984-06	1984-10	-0.51	-2.06	4
	6	1875-03	1875-06	-0.15	-0.45	3
	7	1855-01	1855-03	-0.28	-0.56	2
	8	1855-11	1856-01	-0.17	-0.35	2
	9	1856-03	1856-05	-0.06	-0.12	2
	10	1873-12	1874-02	-0.14	-0.28	2

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m^3/s^1 deficit*	*Accumulated Q95 m^3/s^1 Deficit*	*Drought duration months*
35005 West BFI (0.61)	1	1864-02	1864-11	-1.08	-9.70	9
	2	1953-01	1953-08	-1.69	-11.85	7
	3	1956-02	1956-07	-1.17	-5.87	5
	4	1941-07	1941-11	-0.60	-2.41	4
	5	1856-10	1857-01	-1.37	-4.11	3
	6	1890-05	1890-08	-0.07	-0.22	3
	7	1891-02	1891-05	-1.17	-3.51	3
	8	1893-06	1893-09	-0.02	-0.05	3
	9	1929-04	1929-07	-0.73	-2.20	3
	10	1864-02	1864-11	-1.08	-9.70	9

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m^3/s^1 deficit*	*Accumulated Q95 m^3/s^1 Deficit*	*Drought duration months*
27002 West BFI (0.70)	1	1891-02	1891-08	-0.57	-3.40	6
	2	1893-04	1893-10	-0.24	-1.42	6
	3	1953-02	1953-08	-1.25	-7.51	6
	4	1879-11	1880-03	-1.34	-5.38	4
	5	1887-06	1887-10	-0.17	-0.67	4
	6	1895-06	1895-10	-0.19	-0.78	4
	7	1944-03	1944-07	-0.41	-1.64	4
	8	1902-08	1902-11	-0.38	-1.14	3
	9	1905-07	1905-10	-0.21	-0.62	3
	10	1933-10	1934-01	-3.47	-10.41	3

Catchment	Rank	Drought Start	Drought end	Mean Q95 m³/ s¹ deficit	Accumulated Q95 m³/ s¹ Deficit	Drought duration months
26018 West BFI (0.72)	1	1921-05	1921-12	-0.26	-1.84	7
	2	1893-04	1893-10	-0.02	-0.12	6
	3	1953-02	1953-08	-0.22	-1.31	6
	4	1891-02	1891-06	-0.32	-1.27	4
	5	1941-07	1941-11	-0.03	-0.13	4
	6	1944-03	1944-07	-0.14	-0.55	4
	7	1858-01	1858-04	-0.03	-0.08	3
	8	1870-07	1870-10	-0.03	-0.08	3
	9	1879-11	1880-02	-0.33	-0.98	3
	10	1887-06	1887-09	-0.03	-0.08	3

Catchment	Rank	Drought Start	Drought end	Mean Q95 m³/ s¹ deficit	Accumulated Q95 m³/ s¹ Deficit	Drought duration months
25006 Midlands BFI (0.71)	1	1887-07	1888-04	-1.29964	-11.6968	9
	2	1850-01	1850-08	-1.71125	-11.9788	7
	3	1864-04	1864-10	-0.29988	-1.79925	6
	4	1973-03	1973-09	-1.00088	-6.00525	6
	5	1976-04	1976-10	-0.83921	-5.03525	6
	6	1891-02	1891-07	-1.4809	-7.4045	5
	7	1953-03	1953-08	-0.63385	-3.16925	5
	8	2004-05	2004-10	-0.4824	-2.412	5
	9	1911-06	1911-10	-0.10513	-0.4205	4
	10	1956-04	1956-08	-0.25294	-1.01175	4

Catchment	Rank	Drought Start	Drought end	Mean Q95 m³/ s¹ deficit	Accumulated Q95 m³/ s¹ Deficit	Drought duration months
23002 Southwest BFI (0.31)	1	1893-03	1893-08	-0.61	-3.06	5
	2	1902-07	1902-11	-0.82	-3.27	4
	3	1933-09	1934-01	-2.63	-10.53	4
	4	1953-03	1953-07	-1.95	-7.78	4
	5	1971-05	1971-09	-0.15	-0.60	4
	6	1879-11	1880-02	-2.97	-8.91	3
	7	1887-06	1887-09	-0.33	-0.98	3
	8	1895-05	1895-08	-0.31	-0.92	3
	9	1929-04	1929-07	-0.37	-1.12	3
	10	1852-04	1852-06	-0.15	-0.31	2

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/ s¹ deficit*	*Accumulated Q95 m³/ s¹ Deficit*	*Drought duration months*
19001 South BFI (0.68)	1	1944-02	1944-09	-0.16	-1.13	7
	2	1887-05	1887-11	-0.06	-0.36	6
	3	1906-12	1907-05	-0.51	-2.55	5
	4	1975-04	1975-09	-0.09	-0.45	5
	5	1854-03	1854-07	-0.05	-0.21	4
	6	1854-11	1855-03	-0.85	-3.39	4
	7	1874-06	1874-10	-0.06	-0.25	4
	8	1891-02	1891-06	-0.20	-0.81	4
	9	1921-06	1921-10	-0.05	-0.21	4
	10	1953-01	1953-05	-0.32	-1.29	4

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/ s¹ deficit*	*Accumulated Q95 m³/ s¹ Deficit*	*Drought duration months*
16009 South BFI (0.63)	1	1887-05	1887-11	-1.25	-7.50	6
	2	1921-07	1922-01	-4.12	-24.70	6
	3	1854-11	1855-03	-5.28	-21.10	4
	4	1864-06	1864-10	-0.07	-0.29	4
	5	1893-04	1893-08	-1.62	-6.49	4
	6	1850-01	1850-04	-5.27	-15.80	3
	7	1854-03	1854-06	-3.23	-9.70	3
	8	1874-05	1874-08	-0.31	-0.94	3
	9	1879-11	1880-02	-6.31	-18.94	3
	10	1884-09	1884-12	-3.29	-9.87	3

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/ s¹ deficit*	*Accumulated Q95 m³/ s¹ Deficit*	*Drought duration months*
13002 Southeast BFI (0.73)	1	1975-12	1976-10	-0.20	-1.98	10
	2	1887-06	1888-01	-0.07	-0.51	7
	3	1891-02	1891-08	-0.12	-0.73	6
	4	1893-06	1893-12	-0.04	-0.27	6
	5	1944-03	1944-09	-0.02	-0.10	6
	6	1906-12	1907-05	-0.22	-1.08	5
	7	1975-05	1975-10	-0.03	-0.14	5
	8	1888-02	1888-06	-0.12	-0.49	4
	9	1953-01	1953-05	-0.05	-0.21	4
	10	1854-12	1855-03	-0.17	-0.52	3

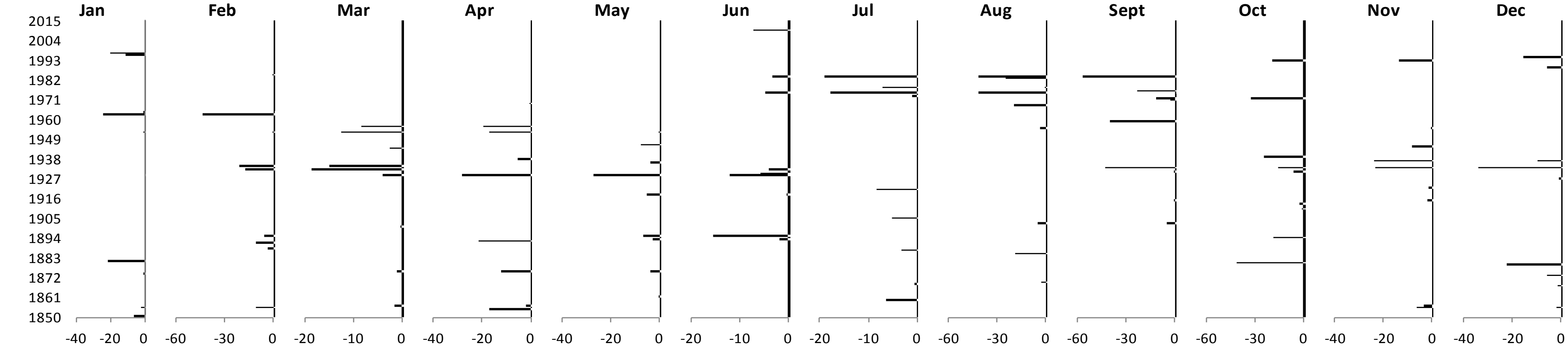
Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/ s¹ deficit*	*Accumulated Q95 m³/ s¹ Deficit*	*Drought duration months*
12001 Southeast BFI (0.72)	1	1893-06	1894-01	-1.43	-10.01	7
	2	1944-03	1944-10	-1.05	-7.38	7
	3	2015-01	2015-08	-1.03	-7.19	7
	4	1887-07	1888-01	-0.42	-2.55	6
	5	1953-02	1953-07	-1.15	-5.75	5
	6	1874-06	1874-10	-0.39	-1.58	4
	7	1891-03	1891-07	-1.09	-4.36	4
	8	1907-01	1907-05	-5.19	-20.77	4
	9	1941-07	1941-11	-0.36	-1.42	4
	10	1854-12	1855-03	-3.58	-10.74	3

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/ s¹ deficit*	*Accumulated Q95 m³/ s ¹ Deficit*	*Drought duration months*
10002 Southeast BFI (0.54)	1	1893-04	1893-12	-0.77	-6.18	8
	2	1874-04	1874-08	-0.41	-1.63	4
	3	1953-01	1953-05	-0.53	-2.13	4
	4	1976-05	1976-09	-0.38	-1.53	4
	5	1884-10	1885-01	-1.11	-3.34	3
	6	1906-12	1907-03	-1.17	-3.51	3
	7	1938-04	1938-07	-0.57	-1.70	3
	8	1944-06	1944-09	-0.06	-0.19	3
	9	1978-09	1978-12	-0.92	-2.77	3
	10	1854-03	1854-05	-0.13	-0.26	2

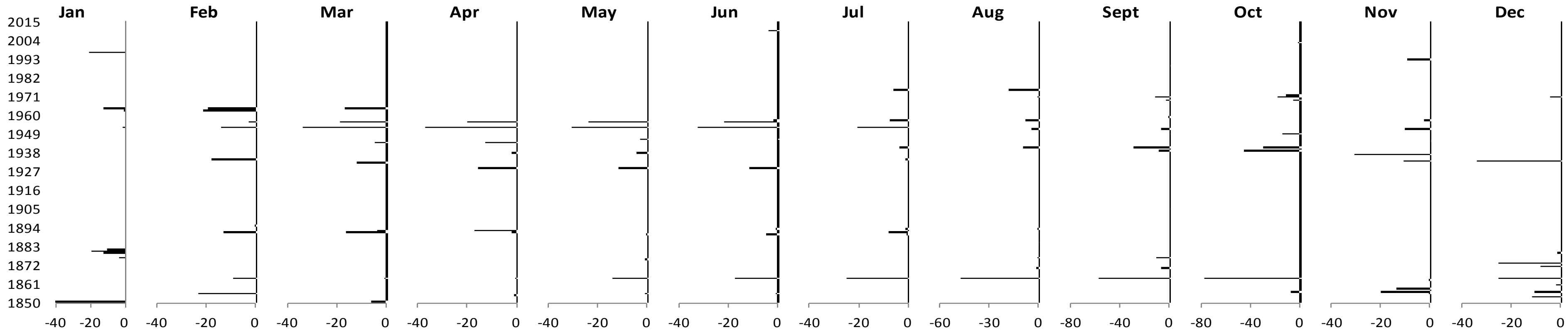
Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/ s¹ deficit*	*Accumulated Q95 m³/ s¹ Deficit*	*Drought duration months*
7012 East BFI (0.68)	1	1891-01	1891-09	-6.48	-51.82	8
	2	1893-06	1894-01	-3.31	-23.19	7
	3	1934-02	1934-09	-6.12	-42.82	7
	4	1953-02	1953-09	-2.22	-15.56	7
	5	1857-12	1858-04	-1.69	-6.75	4
	6	1887-07	1887-11	-0.78	-3.12	4
	7	1892-03	1892-07	-0.93	-3.72	4
	8	1933-09	1934-01	-3.36	-13.45	4
	9	1870-07	1870-10	-0.62	-1.87	3
	10	1895-05	1895-08	-1.29	-3.88	3

Appendix 7 Supplementary drought information for chapter 5

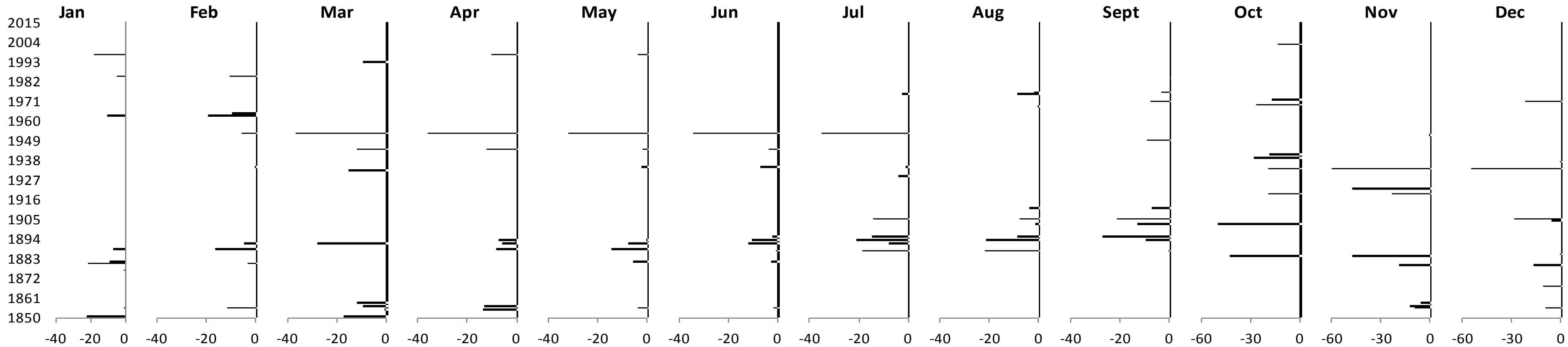
Plots show the months where reconstructed flows fall below the Q95 threshold at all 12 study catchments. The magnitude (x-axis) is the flow as a percentage of the long term Q95 value for that month.



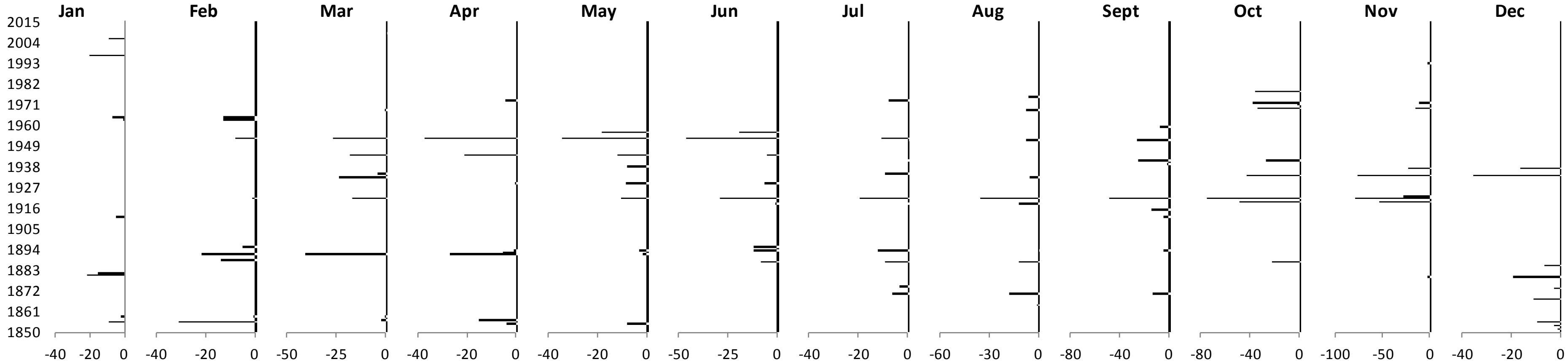
38001 located in the Northwest (BFI = .28)



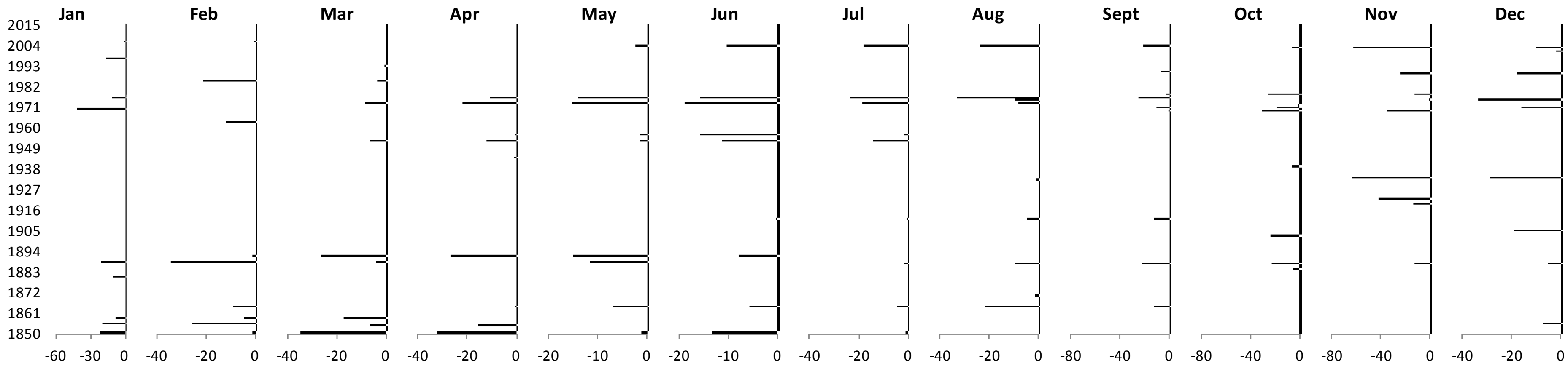
35005 located in the West (BFI = .61)



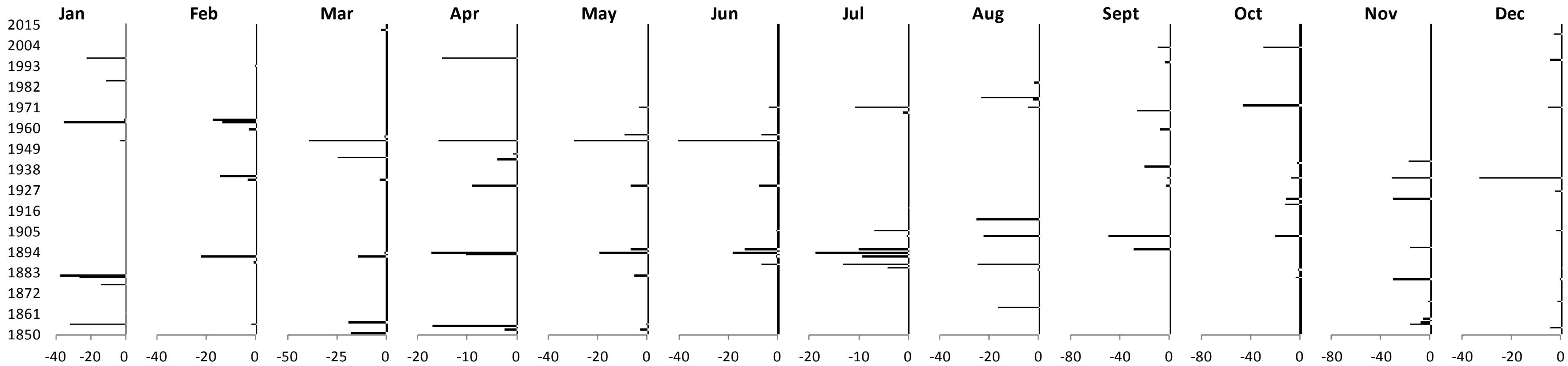
27002 located in the West (BFI = .70)



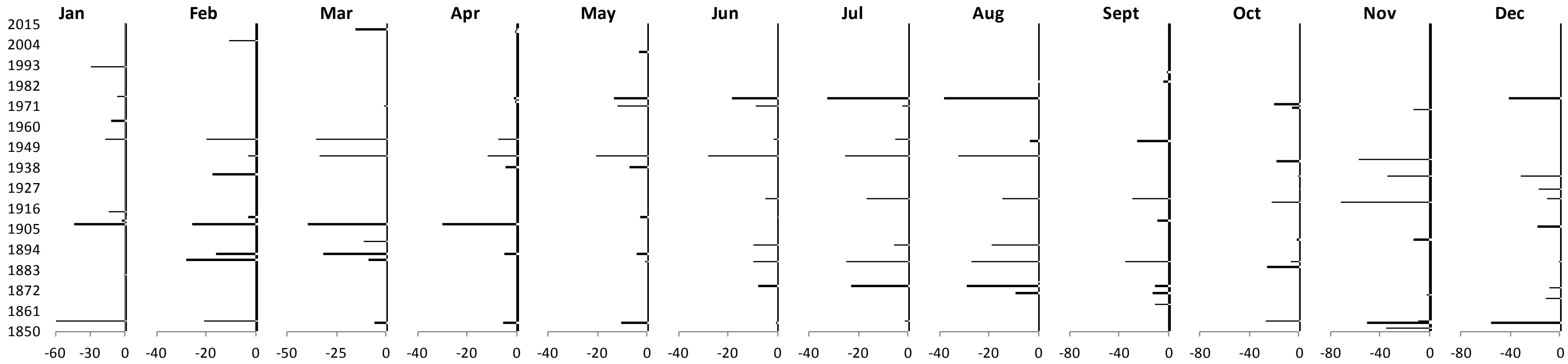
26018 located in the West (BFI = .72)



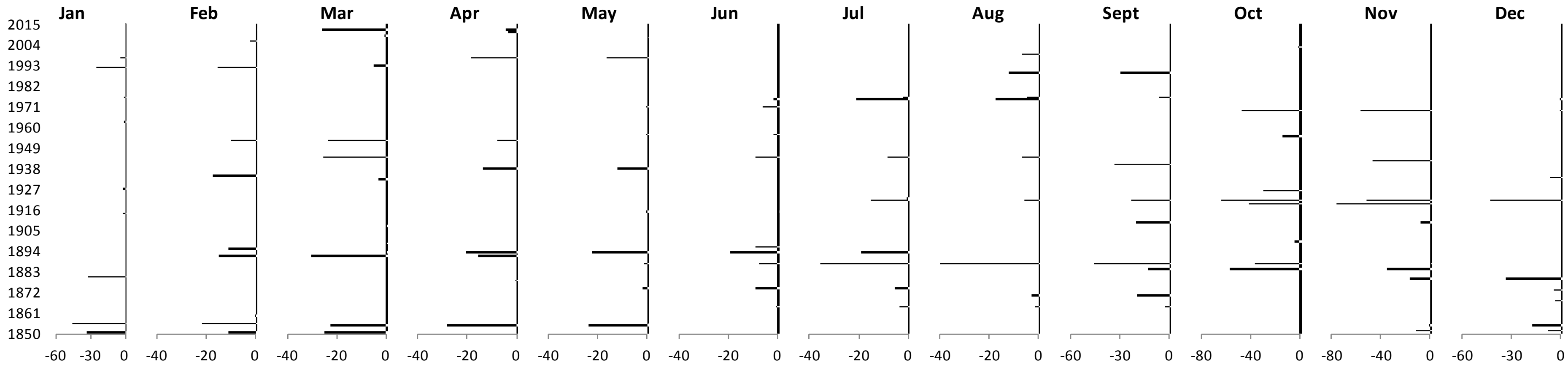
25006 located in the Midlands (BFI = .71)



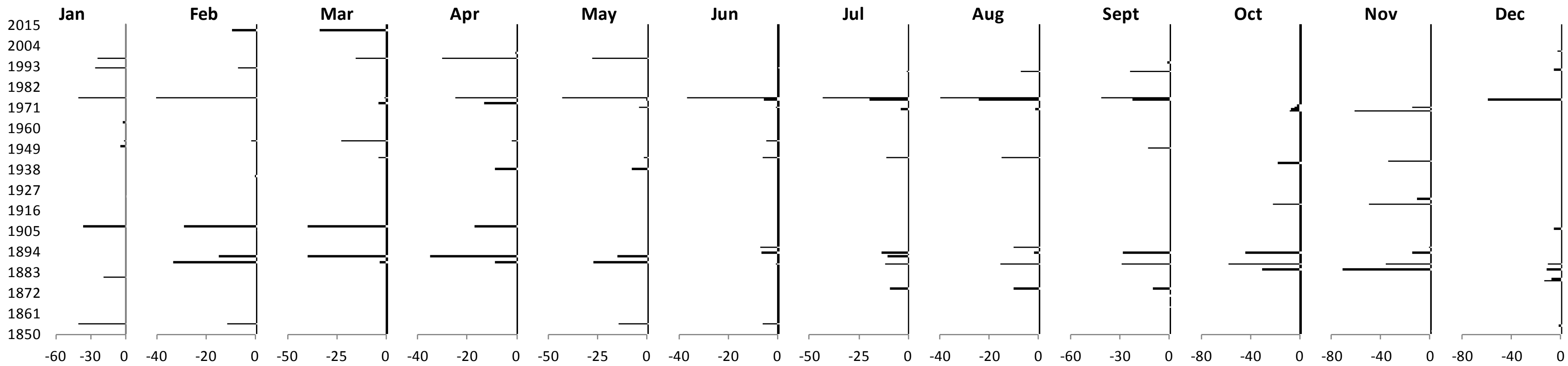
23002 located in the Southwest (BFI = .31)



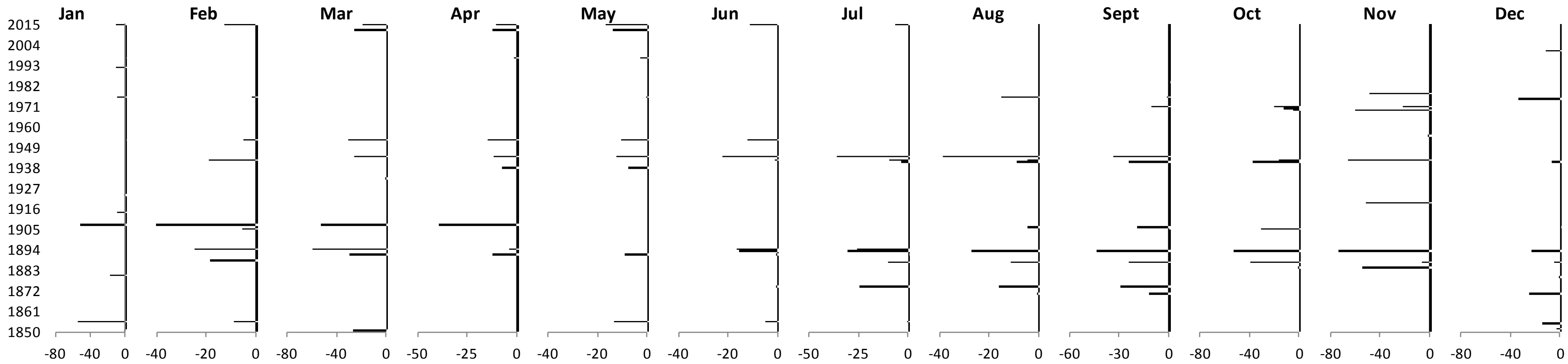
19001 located in the South (BFI = .68)



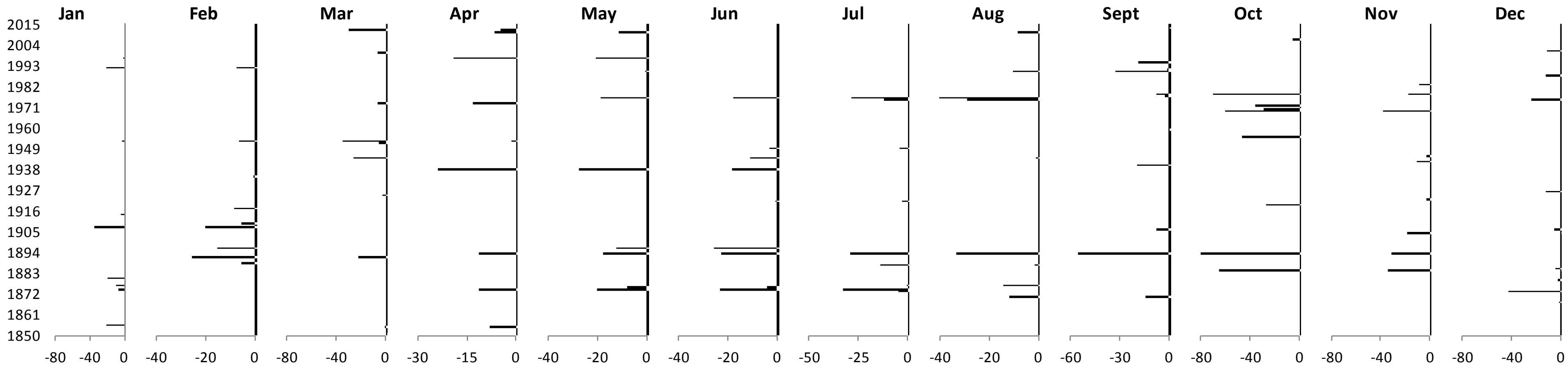
16009 located in the South (BFI = .63)



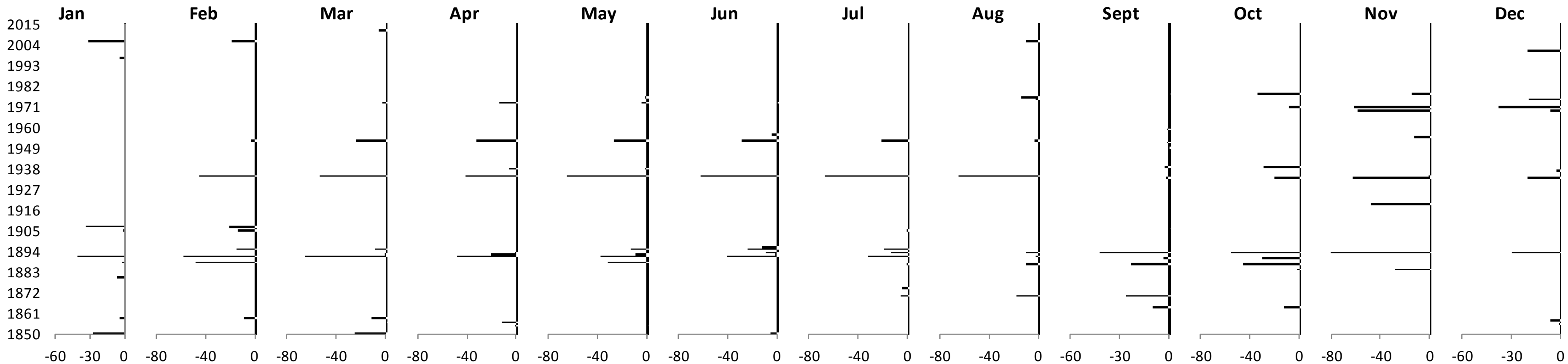
13002 located in the Southeast (BFI = .73)



12001 located in the Southeast (BFI = .72)



10002 located in the Southeast (BFI = .54)



7012 located in the East (BFI = .68)

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