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CROSSDRO: Cross-sectoral Drought Impacts in Complex European Basins

Authors: Conor Murphy and Sam Grainger

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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

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> Large-scale industrial, waste and petrol storage activities;
> Urban waste water discharges;
> The contained use and controlled release of Genetically Modified Organisms;
> Sources of ionising radiation;
> Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

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- Audit and inspection of EPA licensed facilities;
- Drive the implementation of best practice in regulated activities and facilities;
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- Assess and report on public and private drinking water quality;
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- Develop and implement the National Waste Prevention Programme;
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- Publish Ireland's greenhouse gas emission inventories and projections;
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- Produce the State of Ireland's Environment and Indicator Reports;
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- Oversee the implementation of the Environmental Noise Directive;
- Assess the impact of proposed plans and programmes on the Irish environment.

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- Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
- Collaborate with national and EU environmental research activity.

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- Assist in developing national plans for emergencies arising from nuclear accidents;
- Monitor developments abroad relating to nuclear installations and radiological safety;
- Provide, or oversee the provision of, specialist radiation protection services.

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- Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
- Promote the link between health and wellbeing, the economy and a clean environment;
- Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
- Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking

- Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and Structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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Identifying pressures

Droughts are pervasive and hazardous events, which impact multiple domains including agriculture, water resource management, ecological management, infrastructure, waterway navigation and forestry. Ireland's 2018 drought for example had severe impacts across sectors. Agriculture suffered from reduced grass growth, fodder shortages, and decreased crop yield. Peatlands faced increased wildfire risk and ecological degradation. Water management was challenging amid supply issues, low water levels and a heightened demand for resources. Canals, waterways, and rivers experienced weed growth, navigation problems, fishing restrictions, and reduced fish health. Forestry saw increased tree deaths, especially in peatland plantations. Livelihoods were also compromised, with groups such as farmers requiring additional supports.

Informing policy

With these impacts and vulnerabilities in mind, CROSSDRO used high quality observational datasets to assess the changing nature of droughts and their impacts in Europe. In Ireland, specific focus was placed on the Boyne catchment area. Insights from the project have relevance for integrated water management, adaptation to climate variability and change, and drought planning.

Long-term precipitation records indicated increasing meteorological drought trends in Irish summers, particularly in the east, while other seasons and annual trends showed decreasing drought magnitudes. Attribution to anthropogenic climate change remains uncertain due to the dominance of natural variability. The project analysed hydrological drought using river flow gauges, revealing that droughts decreased in winter and increased in late spring and early autumn in Ireland, with significant increases in summer droughts in the Boyne catchment. Arterial and land drainage was found to have minimal impact on hydrological drought in the Boyne catchment, although further analysis using daily flows is needed.

To overcome data limitations, the project utilised newspaper archives from the Irish Drought Impact Database to track and quantify drought impacts. These, together with stakeholder interviews, highlighted the diverse impacts of droughts on agriculture, water management, forestry, waterway navigation, fisheries, and ecosystems, including reduced grass growth, increased water demands, soil degradation, supply issues, weed growth, navigation problems, fishing restrictions, tree deaths, and peatland vulnerability.

Developing solutions

The CROSSDRO project provides recommendations for policy makers to address the vulnerability of sectors and individuals to drought:

1. **Climate change adaptation:** Acknowledge the significant increases in summer drought in Ireland, which are among the highest in Europe. Incorporate drought considerations into local and sectoral adaptation plans, taking into account the cross-sectoral impacts and vulnerability revealed by the 2018 drought and the expected increase in summer droughts due to climate change.
2. **Enhanced monitoring and data collection:** Improve the collection and analysis of meteorological and hydrological data to better understand drought patterns, trends, and impacts. Develop a publicly accessible drought monitor or early warning system in Ireland to identify vulnerable regions, predict drought occurrences, and guide targeted interventions. Monitor and collate societal and economic impacts to assess the effectiveness of drought adaptation strategies.
3. **Extend drought planning:** Complement the National Drought Plan with local drought plans to address spatially variable vulnerability and incorporate diverse stakeholder perspectives into drought planning.
4. **Co-produce knowledge on drought and adaptive responses:** Foster collaboration and knowledge exchange among stakeholders to facilitate better drought management. Move beyond translating scientific knowledge and engage stakeholders in iterative analyses to understand their needs and diverse understanding of droughts, creating more inclusive and effective institutional environments.

Implementing these recommendations could enhance Ireland's capacity to cope with drought events and strengthen resilience across sectors and communities.

EPA RESEARCH PROGRAMME 2021–2030

CROSSDRO: Cross-sectoral Drought Impacts in Complex European Basins

(2019-CCRP-MS.60)

EPA Research Report

Prepared for the Environmental Protection Agency

by

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This report is based on research carried out from December 2019 to March 2023. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Contents

List of Figures

List of Tables

Executive Summary

The AXIS/JPI CROSSDRO project sought to better understand long-term variability and change in droughts and their cross-sectoral impacts on the European and catchment scales, focusing on the Boyne catchment in eastern Ireland. This report details the Irish-relevant findings from the project.

Meteorological Droughts

The CROSSDRO project compiled a long-term dataset (1850–present) of quality-assured precipitation records for the analysis of meteorological droughts across Europe. Long-term precipitation records from across Europe show that trends towards an increase in meteorological drought in the summer months are most notable for Ireland and the UK. These trends are most apparent in the eastern half of the island of Ireland. In other seasons and on an annual timescale, trends indicate decreasing drought magnitude. However, it is important to highlight that a decreasing trend does not negate the possibility of extreme droughts occurring. It is not possible at present to attribute observed trends to anthropogenic climate change given the dominance of natural variability in precipitation records. While an increase in summer droughts is expected with climate change, consistency does not imply causality.

Hydrological Droughts

The CROSSDRO project collated a network of river flow gauges across Europe, covering the period 1962–2017, for the analysis of hydrological drought. For Ireland, trends indicate decreasing hydrological drought in the winter months and increasing hydrological drought in late spring and early autumn. However, these trends are statistically significant for only a few catchments. Negative trends in the duration of drought events predominate in Irish catchments in the period of analysis. The analysis of hydrological droughts from flow reconstructions for the period from 1900 onwards indicates a long-term trend towards increasing drought in the summer, consistent with the analysis of meteorological droughts. On the European scale, the largest increases in hydrological droughts were found in southern Europe, particularly in the Iberian Peninsula. These changes were not driven by precipitation change. Increases in atmospheric evaporative demand with rising temperatures, together with land use changes and increases in water demand, are the most likely drivers.

Drought in the Boyne Catchment

The CROSSDRO project developed a catalogue of meteorological droughts for the Boyne catchment, extending back to 1850. Despite the impacts of the 2018 drought, this drought event does not rank in the top 10 most severe drought events from long-term records. The Boyne catchment has been extensively affected by arterial and land drainage. Our analysis found that these disturbances have had limited impact on hydrological drought in the catchment. We show that newspaper archives can be used to assess the socio-economic impacts of historical droughts on the catchment scale. In addition, we show that drought impacts recorded in newspaper archives can be used to identify which drought metrics and accumulation periods best match impacts in specific sectors. This could inform the development of drought monitoring strategies.

Impacts and Management of Droughts

Interviews with stakeholders in the Boyne catchment and nationally highlighted diverse perspectives on drought and the range of impacts experienced across sectors, including water management, agriculture, forestry, waterway navigation and fisheries, and in relation to ecosystems. For agriculture, droughts were reported as having significant effects on grass growth, fodder management and costs, water demands in the dairy sector, and yields in arable farming and horticulture. Interviewees also highlighted how national strategies have created vulnerabilities through increases in the number of dairy cattle and the associated demands on and costs of water and fodder during droughts, and soil degradation in arable farming.

For water management, droughts were associated with supply issues, especially for private wells and group water schemes. Reduced water levels created problems for abstraction sources, reduced water quality and increased competition for resources. For canals and waterways, droughts were associated mainly with problems of weed growth, navigation and increased competition for resources, while river droughts were associated primarily with restrictions on fishing and reduced fish health. For forestry, stakeholders highlighted the association of drought with tree deaths, with problems in particular for trees in free-draining mineral soils.

The co-production of knowledge on droughts facilitates better management. By moving beyond merely translating scientific knowledge and, instead, iteratively analysing stakeholder needs and explicitly recognising stakeholders' diverse understanding of droughts, more enabling institutional environments can be created. Key challenges include differences in the meaning of drought for different stakeholders, the perceptually challenging and context-specific nature of droughts, and the difficulties in predicting the occurrence, magnitude and duration of droughts.

1 Introduction

Drought is complex, making it one of the most difficult hydroclimatic hazards to quantify and analyse (Wilhite and Pulwarty, 2017). It is also difficult to identify all drought impacts, given the number of natural systems and socio-economic sectors affected. Moreover, scientific debate about recent drought trends (Roderick *et al*., 2015; Dai and Zhao, 2017; Vicente-Serrano *et al*., 2020) adds an important source of uncertainty to the management of these complex hazards. During the last 20 years, drought losses have amounted to €6.2 billion per year in Europe (Van Loon *et al*., 2016). In Ireland, the 2018 drought highlighted the vulnerability of agriculture, water resources and water quality across the island to drought impacts. Cereal yields in 2018 fell by 20% relative to 2017, while dairy farmers experienced a 34% drop in average net margins, with expenditure on animal feed nearly 50% higher in 2018 than in 2017 (Dillon *et al*., 2019; Falzoi *et al*., 2019). In the water sector, the 2018 drought resulted in widespread hosepipe bans, reliance on water tankers to meet potable water needs in some locations and degraded water quality, with impacts for ecosystems and species.

Climate change is likely to affect the frequency, magnitude and duration of droughts. Meresa and Murphy (2023), as part of the EPA HydroPredict project, evaluated climate change impacts on droughts for Ireland. Using the Coordinated Regional Climate Downscaling Experiment (CORDEX) ensemble of regionalised climate models to examine changes in droughts expected by the 2080s, they found that drought magnitude, frequency and duration would increase, particularly when they used indices that account for evaporative losses. These increases were also found to be greater if models were based on high greenhouse gas emission pathways than if they were based on more moderate emission pathways. The greatest changes in drought magnitude were predicted for summer, especially in the east and midlands. Given the vulnerability exposed by the 2018 drought and the expectation of more severe and frequent droughts with climate change, it is critical to develop deeper insights into changes in observed drought events, impacts, stakeholder needs and management approaches.

The CROSSDRO project (funded by the EPA via the European AXIS Joint Call for Transnational Collaborative Research Projects 2018 on Assessment of Cross(X)-sectoral Climate Impacts and Pathways for Sustainable Transformation) sought to advance scientific understanding of droughts in complex river catchments and on the European scale, and to develop practical guidance on drought management through the engagement of key stakeholders throughout the work. The project brought together researchers from Ireland (Irish Climate Analysis and Research Units (ICARUS), Maynooth University), Spain (Spanish National Research Council), Germany (Potsdam Institute for Climate Impact Research), Sweden (Lund University) and Moldova (Selectia Research Institute of Field Crops) with experience of assessing drought on national and continental scales. Research took a cross-scale perspective, focusing on complex catchments in each partner country and assessing changes in drought on the European scale. The catchments included (1) the upper Aragón catchment in north-east Spain, (2) the German part of the Elbe catchment, (3) the Boyne basin in Ireland and (4) the Moldovan part of the Prut catchment. While the project generated several published papers and datasets, this report focuses on key outputs with relevance for Ireland. For the interested reader, Appendix 1 provides references for all project outputs. Relevant parts of this report are taken from papers produced from the project, with links providing access to further information as necessary. Further details about the project can be found on the website hosted by the lead partner in Spain (https://crossdro.csic.es/).

This report is structured as follows:

- Chapter 2 focuses on work undertaken to understand drought variability and change on the European scale. We focus on meteorological and hydrological droughts and the results of analyses undertaken on two new datasets compiled by the project. The chapter draws out key changes in droughts and their characteristics across Europe, and contextualises changes in Ireland within the broader European picture.

- Chapter 3 moves attention to understanding drought in the Boyne catchment, detailing work to develop a drought catalogue for the catchment extending back to 1850, contextualising the recent 2018 event in terms of historical droughts, understanding the impacts of arterial drainage on drought and the cross-sectoral impacts of drought events, and linking drought metrics with impacts in the catchment. For drought impacts, we make novel use of newspaper archives.
- A key part of the CROSSDRO project was working with stakeholders, to understand their experience of droughts. Chapter 4 details the results of interviews undertaken with key stakeholders and policymakers in the Boyne catchment and nationally. The chapter provides insights into key impacts of droughts across sectors, adaptation strategies undertaken during drought events and challenges for management.
- Given the challenges in defining droughts and their complex impacts across sectors, Chapter 4 also examines key opportunities for and barriers to co-producing knowledge for better drought management. These insights are based on a literature review, experience across the project team and insights from stakeholder engagement work.
- Finally, Chapter 5 distils key conclusions and recommendations from across the report.

2 Drought Variability and Change on the European Scale

2.1 Introduction

This chapter investigates variability and change in meteorological and hydrological droughts on the European scale, contextualising changes observed in Ireland within a broader European context. Long-term (1851–2018) trends in meteorological droughts and their characteristics were analysed over western Europe using 199 homogenised monthly rainfall records, to identify spatial patterns of change and to examine if changes in the duration, magnitude and spatial extent of droughts are evident. To investigate hydrological droughts, the CROSSDRO project identified a long-term, high-density network of 3324 river flow gauging stations across Europe for the period 1962–2017. The following sections provide an overview of the datasets developed, methods deployed and key results. Full details of the assessment of meteorological and hydrological droughts can be found in papers published by Vicente-Serrano *et al*. (2021a) and Peña-Angulo *et al*. (2022), respectively.

2.2 Data and Methods

2.2.1 Meteorological droughts

The CROSSDRO project developed a new precipitation dataset, comprising 199 homogenised monthly data series from across western Europe (Figure 2.1). Data were compiled from national meteorological agencies, the Global Historical Climatology Network and the European Climate Assessment & Dataset project. Irish data were taken from the Island of Ireland Precipitation network (Noone *et al*., 2016). Selected time series were subjected to quality control and homogeneity testing using HOMER (HOMogenisation softwarE in R) (Venema *et al*., 2012). The final dataset comprised data from 115, 171 and 199 precipitation stations, with records dating back to 1851, 1861 and 1871, respectively. Meteorological droughts were investigated using the Standardised Precipitation Index (SPI), fitted using a gamma distribution (McKee *et al*., 1993; Beguería *et al*., 2014). The SPI was computed on 3- and

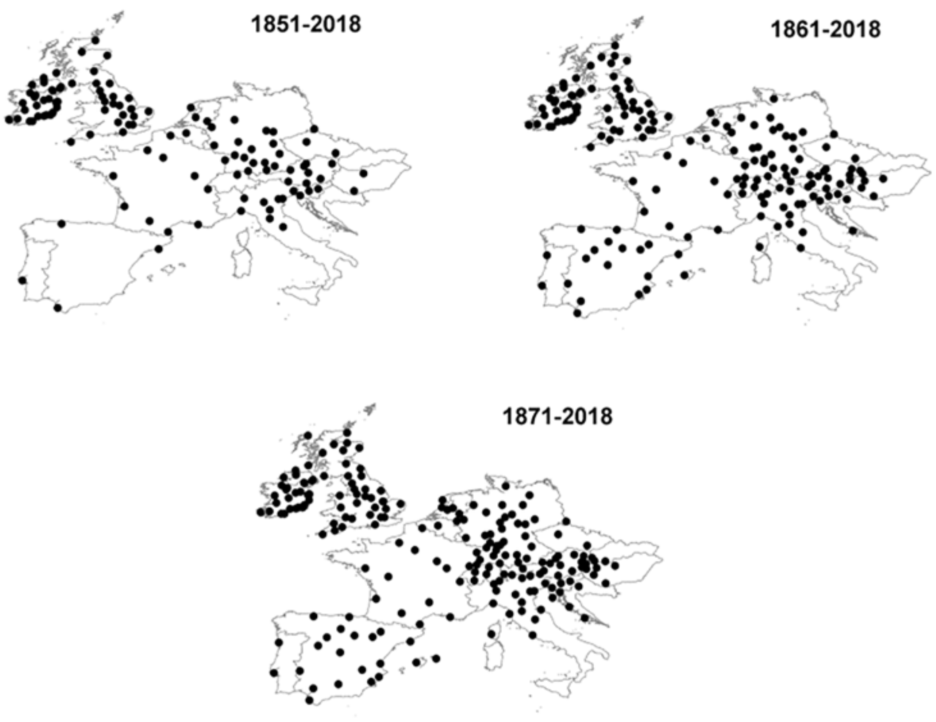

Figure 2.1. Spatial distribution of precipitation stations employed for each period of analysis. Source: reproduced from Vicente-Serrano *et al.* (2021a).

12-month timescales (SPI-3 and SPI-12, respectively), to examine seasonal and annual drought, respectively. Drought characteristics were also evaluated for individual events: the SPI value falling below –0.84 was used to indicate a drought event commencing and the SPI value recovering to zero was used to indicate a drought event terminating. Drought duration is defined as the number of consecutive months in drought. The accumulated deficit, used as a measure of severity, is taken as the sum of SPI values during a drought event. Finally, the spatial extent of drought events was investigated using a Thiessen polygon method, to account for the unequal distribution of precipitation stations in space. The total surface area affected by drought annually was calculated for three different drought categories: mild, moderate and severe events.

Trends in the seasonal and annual SPI series, drought magnitude, duration and surface area were assessed using ordinary least squares regression, with statistical significance (at the 0.05 level) assessed using a modified version of the non-parametric Mann–Kendall (MK) test that limits the impact of potential autocorrelation in the data. Trends were calculated for SPI-3, that is, at 3-month intervals, in February, May, August and November, representing winter, spring, summer and autumn, respectively. SPI-12, computed in December, was used to characterise drought on the annual scale. Principal component analysis was used to determine homogeneous regions in terms of drought variability, with the most representative station of each component used to represent interannual variability in drought conditions. Trends were evaluated and mapped for the full period of record (1871–2019) and for different combinations of start and end dates, to explore the sensitivity of trend results to the length of record tested.

2.2.2 Hydrological droughts

A European streamflow dataset was compiled to analyse hydrological droughts. Monthly streamflow data were obtained from hydrometric agencies across Europe for the period 1962–2017. Gaps in the series were infilled using a regression technique and a reference series composed of data from nearby stations. A total of 3324 river flow gauging stations were included in the final dataset, representing a wide range of catchment characteristics across Europe (Figure 2.2). The Standardised Streamflow Index (SSI) was used to identify hydrological droughts, with six different distributions evaluated for fitting, with the best-performing distribution selected on a case-by-case basis. As with the SPI, a threshold of –0.84 was selected to identify the onset of a drought event.

The severity, frequency and duration of droughts were quantified. Frequency is defined as the number of events per year, while duration refers to number of months from drought onset (SSI = –0.84) to termination (SSI = 0). Severity is defined as the accumulated deficit between drought onset and termination. Trend analysis, using the same methods as described for meteorological drought (see section 2.2.1), was conducted on monthly SSI series, together with

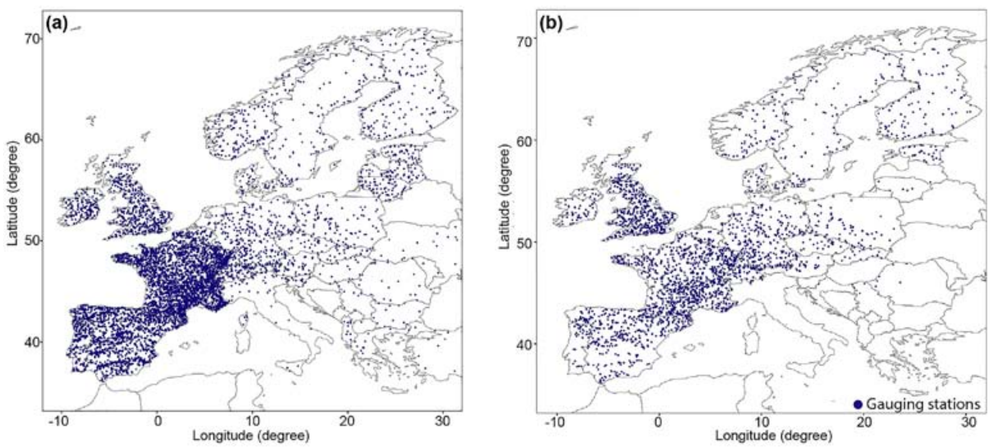

Figure 2.2. Spatial distribution of river flow gauging stations: (a) all stations included in the database and (b) stations selected for data analysis. Source: reproduced from Peña-Angulo *et al.* (2022); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

analyses of the annual duration, frequency and severity of drought events for the period 1962–2017.

2.3 Results

2.3.1 Seasonal trends in meteorological drought frequency

Long-term SPI trends on the annual scale (December SPI-12) are shown in Figure 2.3. Statistically significant positive trends (i.e. conditions getting wetter) are evident for Ireland, the UK and central Europe from 1851, while negative trends (i.e. conditions getting drier) predominate in Italy and the Balkans. If the start date of the analysis is changed to 1871, trends in north-west Europe are less consistent, indicating the importance of the study period for trend results. Across Europe, the percentage of stations with positive trends is greater than the percentage of stations with negative trends, irrespective of study period. In winter (not shown), trends derived from February SPI-3 are mostly positive, with the largest changes in central areas of western Europe. Very few stations exhibit statistically significant negative trends in winter. In spring (not shown), trends derived from May SPI-3 show large spatial variability. Positive trends predominate in Ireland and the UK, northern France and Germany, with negative trends predominating in the south-west of the Iberian Peninsula, Italy and the Balkans. However, in most cases, these trends are non-significant and are sensitive to the period of analysis used.

Summer (August SPI-3) shows the largest percentage of stations with negative trends (i.e. increased drought), especially in Ireland and the UK (Figure 2.4). In autumn (November SPI-3; not shown), trends are generally non-significant, but a significant positive trend is noted for Irish stations.

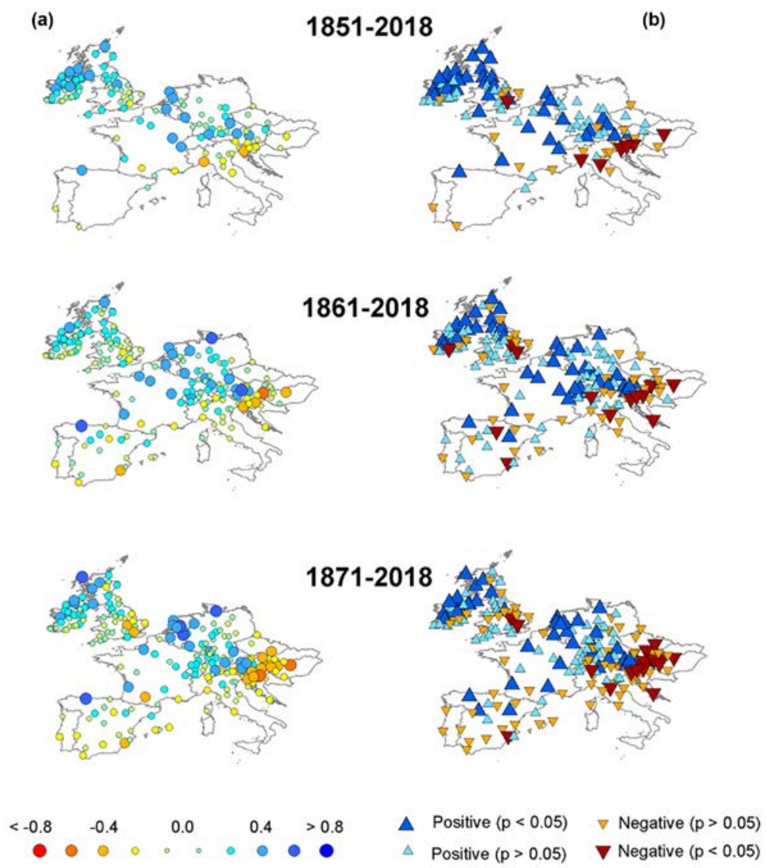

Figure 2.3. Spatial distribution of precipitation stations showing (a) the magnitude of change in annual SPI series (December SPI-12) and (b) the statistical significance of the increasing (positive) and decreasing (negative) trends identified. The magnitude of change is expressed in z-units per decade. Source: reproduced from Vicente-Serrano *et al.* (2021a).

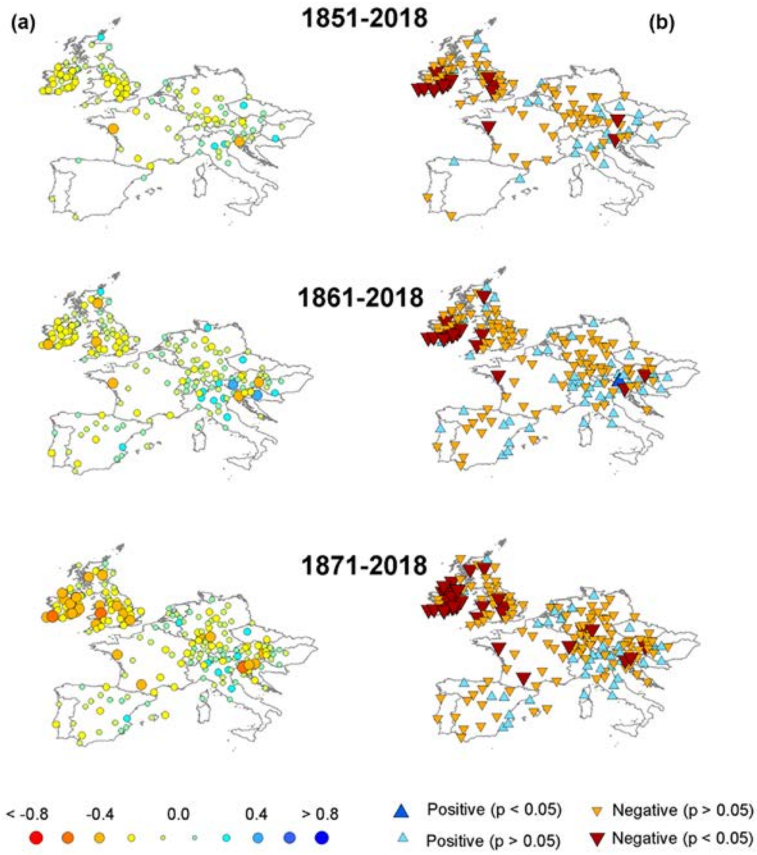

Figure 2.4. Spatial distribution of precipitation stations showing (a) the magnitude of change in summer SPI series (August SPI-3) and (b) the statistical significance of the increasing (positive) and decreasing (negative) summer trends identified. The magnitude of change is expressed in z-units per decade. Source: reproduced from Vicente-Serrano *et al*. (2021a).

2.3.2 Changes in meteorological drought characteristics

No consistent trends in drought event duration and magnitude were found across western Europe using SPI-12. For SPI-3, significant positive trends in drought duration and magnitude (i.e. a tendency towards a longer drought duration and a greater drought magnitude) were found for some stations in the south of Ireland and the UK, the Iberian Peninsula, the Balkans and Italy (Figures 2.5 and 2.6). Conversely, negative trends were found for Northern Ireland, Scotland and eastern France.

2.3.3 Spatial and temporal components of meteorological droughts

Given the spatial diversity of the long-term SPI series on the seasonal and annual timescales, principal component analysis was applied to delineate the main patterns of drought from 1871 to 2018. The results suggest coherent spatial patterns, with clear linkages to climate conditions across western Europe. We retained 23 components, which together contribute more than 75.2% of the total variance. Vicente-Serrano *et al*. (2021a) provide a full analysis of each component. Here, attention is given to component 1, which represents drought variability over Ireland and is best represented by the data for Cappoquin (Figure 2.7). The most severe drought events were observed during the 1850s, 1920s, 1930s, 1950s and 1970s. For annual, winter, spring and autumn droughts, short-term variability predominates, with the increasing and decreasing trends identified dependent on the period of analysis. Persistent and significant negative trends (i.e. conditions getting drier) are found for summer droughts for tests that start before 1900, indicating the value of long-term records in identifying trends. Few notable changes are evident in the magnitude and duration of droughts over the period of record, although it is evident that the most recent

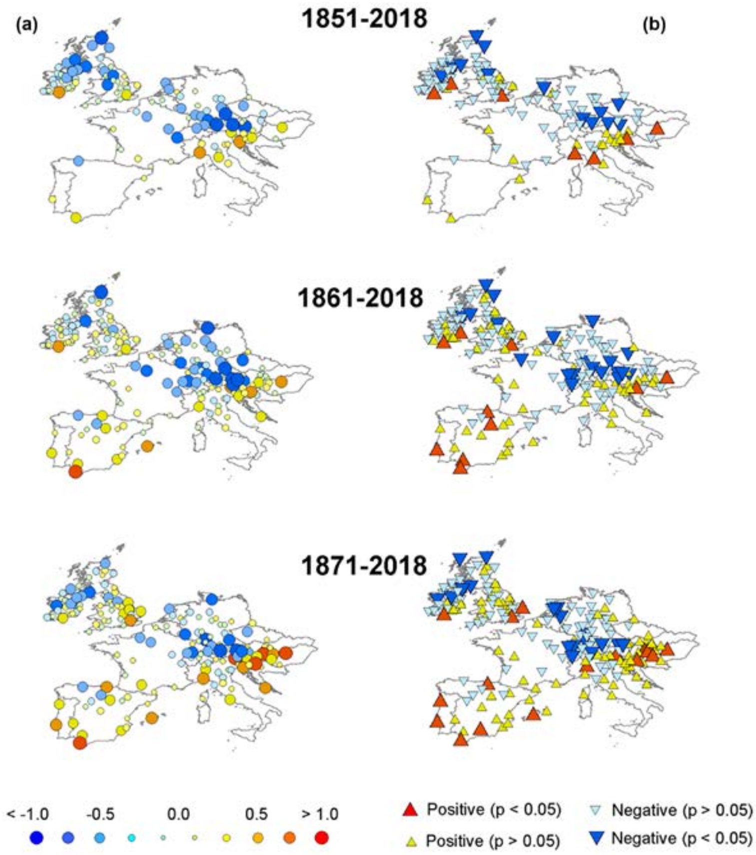

Figure 2.5. Spatial distribution of precipitation stations showing (a) changes in the duration of drought events identified from SPI-3 series and (b) the statistical significance of the increasing (positive) and decreasing (negative) trends identified. Changes in duration are expressed in months per decade. Source: reproduced from Vicente-Serrano *et al.* (2021a).

40 years (≈1980–2018) show an increasing trend in the magnitude and duration of SPI-3 droughts.

2.3.4 Changes in hydrological droughts

Trends in monthly SSI series were evaluated for catchments for the period 1962–2017, with results shown in Figure 2.8. For Ireland, increasing trends in monthly SSI (i.e. decreasing drought) were found for the months of January, February, March and November. Decreasing trends are evident for April and May, and the late summer/early autumn months of August, September and October. The summer months of June and July show weak increasing trends, and for December western catchments show increasing trends and eastern catchments show decreasing trends. Few trends are statistically significant. On the European scale, the most notable changes are decreases in SSI for all months, especially for summer and autumn in southern Europe, most notably in northern Spain and southern France (Figure 2.8).

Considerable differences in the frequency, duration and severity of hydrological drought events are evident across Europe. Negative trends in the duration of drought events were found to predominate for Irish catchments for the period of analysis, which is consistent with trends in northern Europe more broadly, with many significant at the 0.05 level (Figure 2.9). In southern Europe, significant positive trends in drought duration are evident, especially in northern Spain and southern France. In terms of drought frequency (Figure 2.9), the general direction of change is towards decreased frequency, but trends were found to be statistically significant for only a few Irish catchments. A similar pattern of change is evident for northern England and Scotland. An increase in drought frequency is also apparent in southern Europe, being statistically significant in northern Spain and southern France. Finally, in terms of severity (Figure 2.9), negative trends were found to predominate for Ireland, indicating a decreasing trend in drought severity for the period of record, with

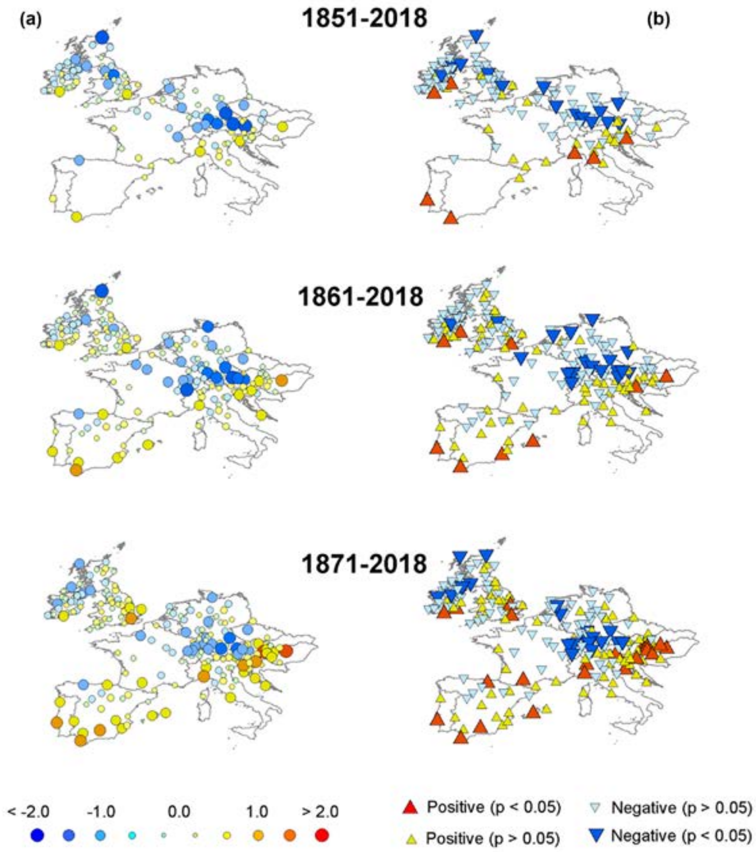

Figure 2.6. Spatial distribution of precipitation stations showing (a) changes in the magnitude of drought events identified from SPI-3 series and (b) the statistical significance of the increasing (positive) and decreasing (negative) trends identified. Changes are expressed in z-units per decade. Source: reproduced from Vicente-Serrano *et al*. (2021a).

a number of these trends being significant. The largest increases in drought severity are again evident for southern Europe, particularly for Spain.

2.4 Discussion and Conclusion

The CROSSDRO project involved a comprehensive assessment of long-term variability and change in meteorological and hydrological droughts for western Europe using datasets for precipitation that extend back to the mid-19th century and river flow records that extend from the 1960s to present. From a long-term perspective, no consistent trends in meteorological droughts are evident across Europe. The most notable long-term trends in meteorological droughts were identified for Ireland and the UK in summer, where a long-term trend towards drier conditions was observed, especially from tests on records that commenced prior to 1900. Increasing trends (i.e. less severe droughts) were found annually and for other seasons in these regions.

Our findings seem to contradict previous studies that suggest that drought severity has increased over southern Europe in recent decades (e.g. Hoerling *et al*., 2012; Vicente-Serrano *et al*., 2014; Gudmundsson and Seneviratne, 2016; Stagge *et al*., 2017). These differences might be due to differences in the study period. This issue is of particular importance in trend detection, given that the magnitude and significance of the observed trends can vary considerably as a function of the length of the series and the selected study period (Hannaford *et al*., 2013; Murphy *et al*., 2013). Our assessment of drought characteristics was based on SPI, which is a metric based on only precipitation. Differences with previous studies may also be explained by changes in atmospheric evaporative demand (AED) with increasing temperature. According to Robinson *et al*. (2017), AED has significantly increased in western Europe over recent decades. A similar finding has also been reported by Vicente-Serrano *et al*. (2014) for southern Europe, namely that increasing drought

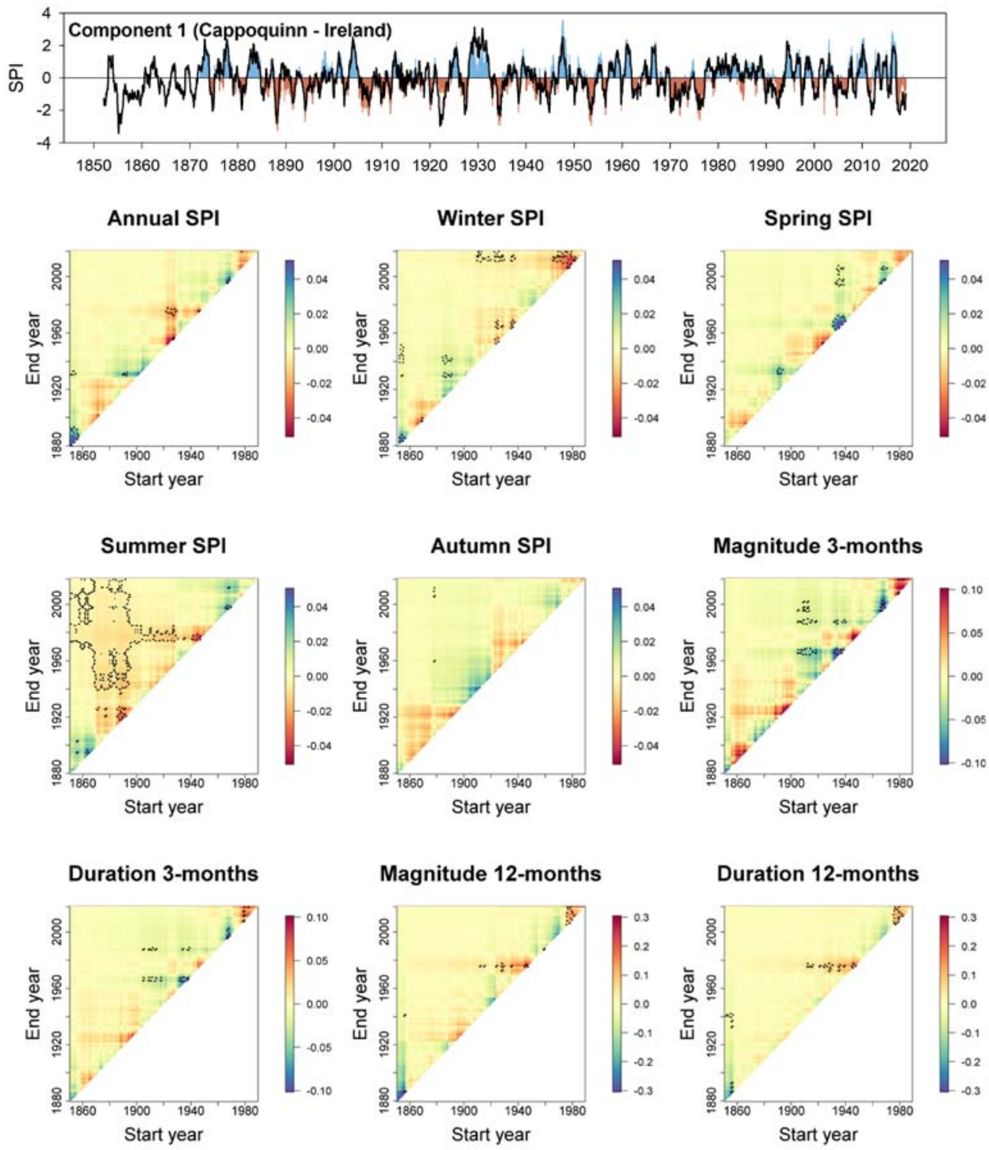

Figure 2.7. Temporal evolution of the SPI-12 series for component 1 (in colour) and the series of the most representative station (Cappoquin, Ireland, black line). The correlation between component 1 and Cappoquin is $r = 0.85$. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for Cappoquin. The *x*- and *y*-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend ($p < 0.05$). Source: reproduced from Vicente-Serrano *et al.* (2021a).

severity is mostly associated with an increase in air temperature and a decline in relative humidity. In addition, Murphy *et al*. (2019, 2020) have shown that pre-1870 winter precipitation in north-west Europe is likely to be underestimated because of the undercatch of snowfall measurements. Such changes that affect multiple stations simultaneously may not be detected using relative homogenisation methods and could affect winter and annual SPI trends for stations in the British and Irish Isles.

Our analysis of hydrological droughts reveals a complex picture of streamflow trends on a continental scale. The differences in trends between regions may be explained by the different physical mechanisms controlling interannual variability in climate and streamflow, such as the North Atlantic Oscillation (e.g. Lorenzo-Lacruz *et al*., 2022). Our findings suggest that climate variability, particularly the impact of winter conditions during the remainder of the year,

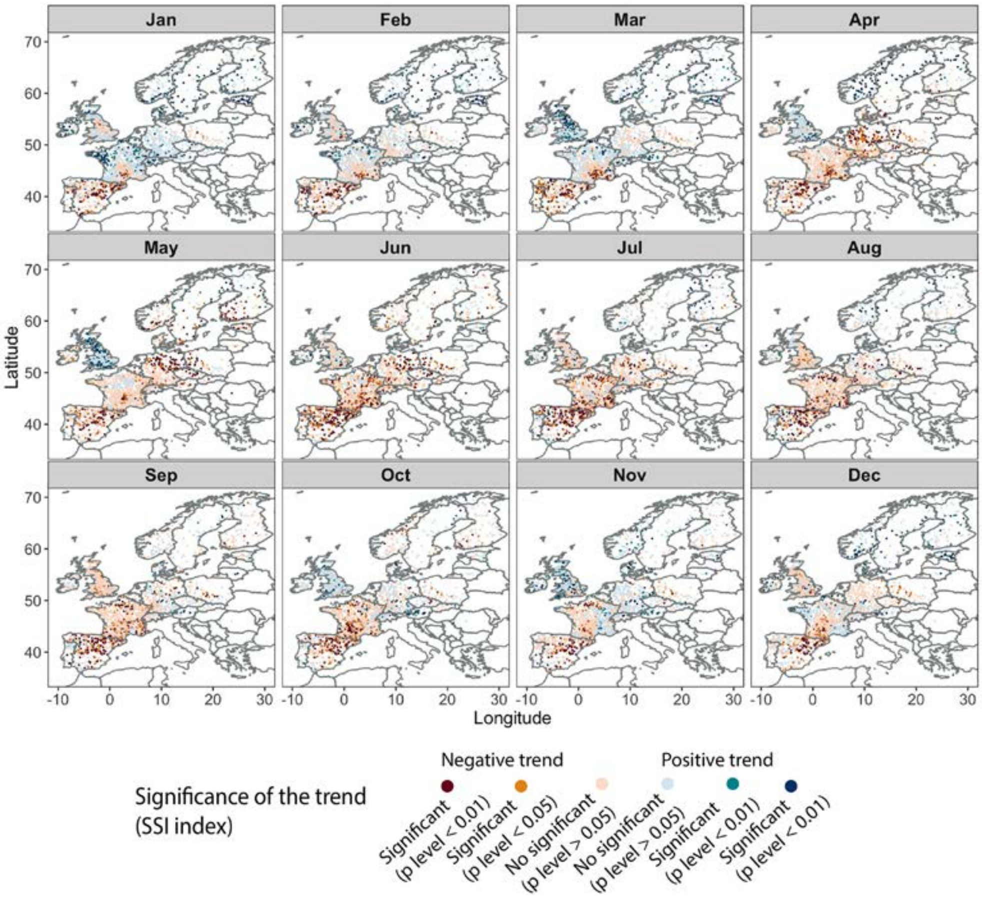

Figure 2.8. Spatial distribution of river flow gauging stations showing the direction and significance of trends identified in monthly SSI series over the period 1962–2017. Each circle represents one gauging station. Source: reproduced from Peña-Angulo *et al*. (2022); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

may play an important role in observed patterns of drought trends (Stagge *et al*., 2017). Other local factors are also likely to be important, including local topography, catchment characteristics and lithology. In broad terms, in northern Europe, streamflow shows increasing trends during the cold season, with predominantly weak or negative trends in late spring and summer months. This is consistent with the findings of Stahl *et al*. (2010). Notably, significant decreasing trends were found for the majority of months in southern Europe, in the Iberian Peninsula and southern France in particular. This contradicts our findings on variability and change in meteorological drought, highlighted above (section 2.3.1).

Additional studies, as part of the CROSSDRO project, sought to unpack these conflicting results. Vicente-Serrano *et al*. (2021b) show that anthropogenic activities, including the revegetation of mountain headwaters in northern Spain and southern France, together with the development of reservoirs for water storage, can explain the decreasing trends in streamflow that are absent in the assessment of precipitation change. In addition to these human activities, a strong influence of increased AED and actual evapotranspiration, driven by rising temperatures, is evident in southern Europe (Tomas-Burguera *et al*., 2021). This increase in AED, together with vegetation regeneration, increases the uptake of water (for evapotranspiration) by vegetation and increases irrigation demand, especially during summer and during dry years. This drives the observed decrease in streamflow, despite a lack of long-term change in precipitation. Vicente-Serrano *et al*. (2021b) detail these processes for an upland catchment in the central Spanish Pyrenees.

In terms of changes in drought severity and frequency, regions of northern Europe show a negative trend in drought characteristics at the annual scale, indicating

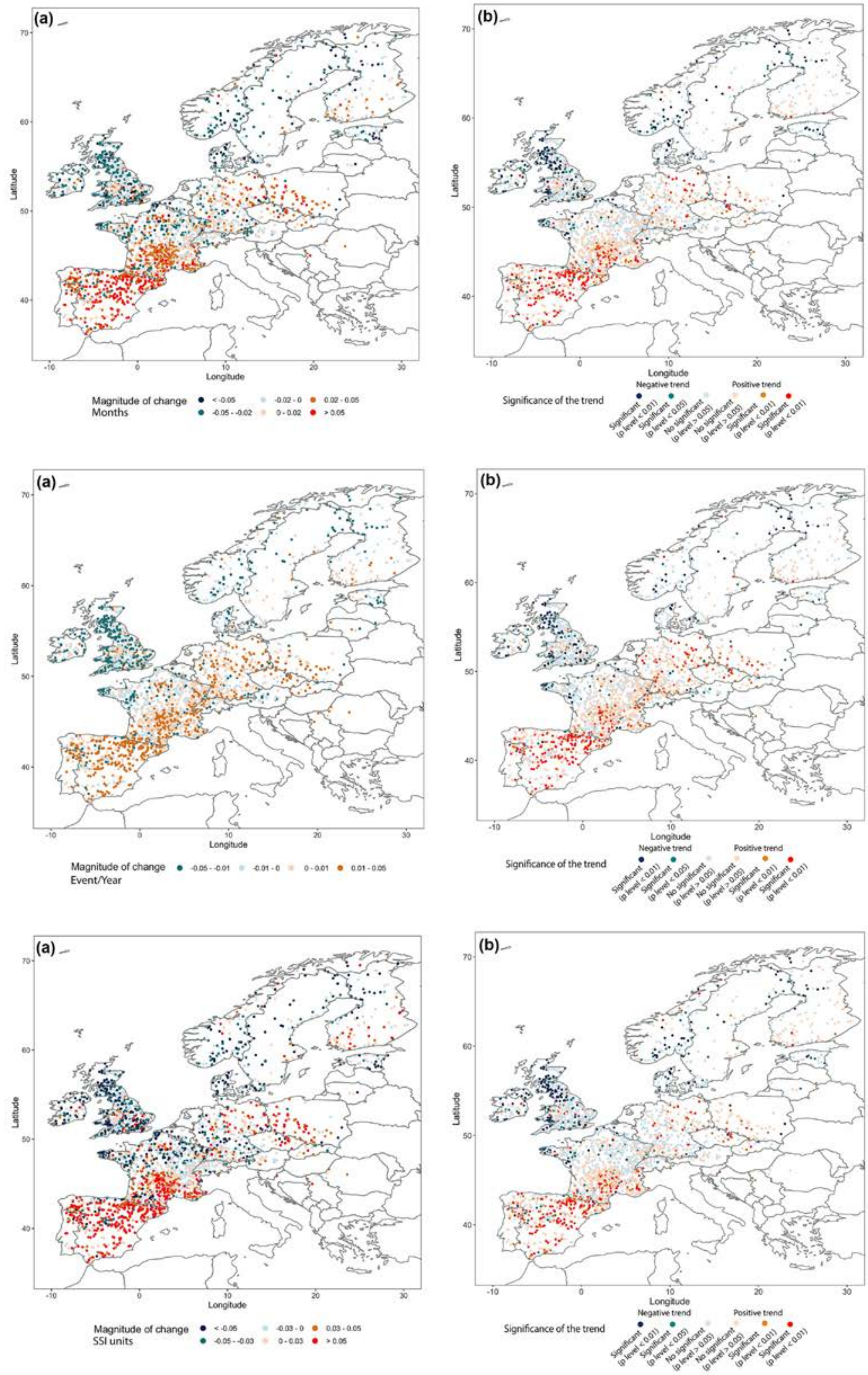

Figure 2.9. Trends in the duration (top row), frequency (middle row) and severity (bottom row) of drought events from 1962 to 2017. Spatial distribution of river flow gauging stations showing (a) the magnitude of changes in SSI and (b) the corresponding significance of the trends identified (at *p* < 0.05 or *p* < 0.01) over the same period. Each circle represents one gauging station. Source: reproduced from Peña-Angulo *et al*. (2022); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

a general decrease in severity. During summer, patterns of change are more complex. Conversely, southern and central Europe show a positive trend in drought characteristics, and a general increase in hydrological drought severity. Increases in drought severity in southern Europe are more than expected due to precipitation change alone, and again point to the impact of revegetation and changes in AED on drought characteristics.

3 Drought in the Boyne Catchment: Historical Droughts and Impacts in a Complex Catchment

3.1 Introduction

A key focus of the CROSSDRO project was to understand drought changes in complex catchments in each partner country. In Ireland, we chose to study the Boyne catchment, given that the catchment experienced significant impacts during the 2018 drought, has good long-term records and has been extensively affected by arterial drainage. This part of the project sought to achieve the following aims and objectives, to better understand drought events and their impacts in the catchment:

- to catalogue historical droughts in the Boyne catchment for the period 1850–present;
- to investigate evidence for trends in meteorological droughts in the catchment;
- to examine the impact of arterial drainage on standardised drought metrics for the catchment;
- to examine sectoral impacts of drought documented in newspaper archives;
- to link drought metrics with impacts on the catchment scale.

3.2 The Boyne Catchment

The Boyne catchment, located in eastern Ireland, has an annual average total precipitation of 897 mm (1952–2009). The catchment drains a land area of 2694 km^2 (Figure 3.1). A long-term river flow gauging site (1941–present) of good quality is located at Slane Castle in County Meath (latitude 53.706870°N, longitude 6.562389°W) and is used in this study to represent flows in the catchment. The catchment area for Slane Castle is 2460 km^2 and the main channel length is 94 km. There are several lakes in the north-west of the catchment, the most significant being Lough Ramor and Mullagh Lake in County Cavan. The catchment can be characterised as being predominantly flat to undulating lowland with elevation ranging between 16 m and 338 m. Land use is dominated by agricultural pastures (87%), with dairy farming being the predominant agricultural enterprise. Other significant land use types are arable agriculture (≈10%), forestry (≈5%) and bogs (≈5%). The catchment is classified as essentially rural, with

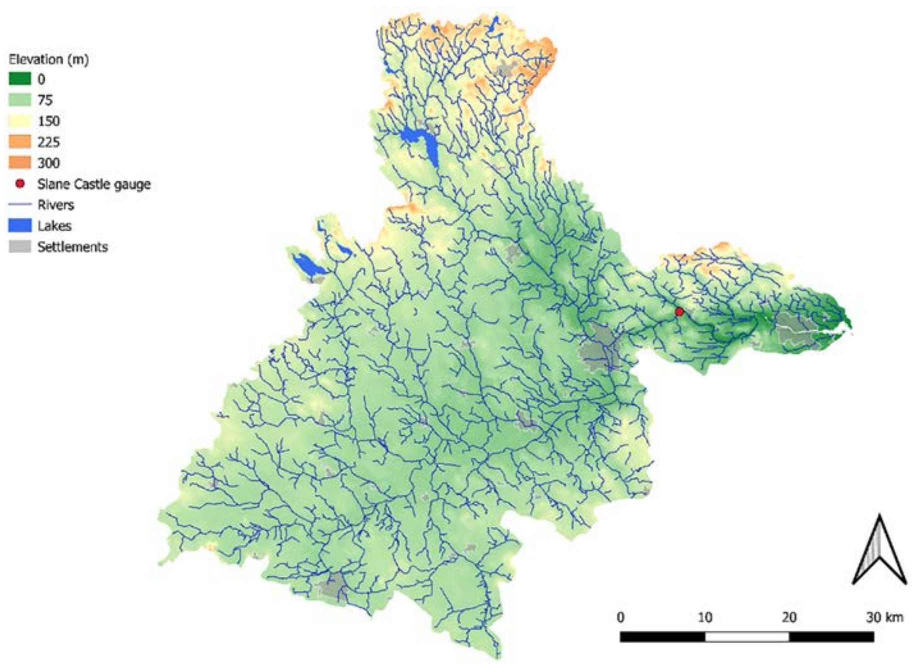

Figure 3.1. The Boyne catchment in eastern Ireland. The red dot marks the location of the river flow-gauging station at Slane Castle.

only approximately 1.5% of the catchment area being urbanised. The main towns in the catchment are Drogheda, Navan, Trim, Kells, Virginia, Bailieborough, Athboy, Kinnegad, Edenderry and Enfield. The total population of the catchment is approximately 196,400, with a population density of circa 73 people per km^2. Water supplies in the catchment are abstracted from 89 sources, including six group water schemes, eight public supplies serving major urban centres and five private supplies. In addition, an unknown number of private boreholes are used for domestic consumption and farm use.

The catchment is underlain by metamorphic rocks in the north and limestone bedrock in the centre and south of the catchment. Extensive areas of sand and gravel are found in the upper reaches of the catchment. Geology and soil types show a similar pattern, with the southern and central parts of the catchment dominated by grey-brown podzolic and gley soil, with significant peat deposits. In the north of the catchment, soils are typically acid brown earth and gley soils. More than 35% of the catchment is composed of poorly drained soils, including basin peat and gley soils.

Given the importance of agriculture in the catchment and the presence of poorly drained soils, the catchment has been subject to extensive arterial and field drainage works. Arterial drainage involves the artificial widening and deepening of main river channels and important tributaries, to improve discharge conveyance (O'Kelly, 1955). Following arterial works, peak flows have been noted to increase and the time to peak and duration of flood hydrographs to shorten (O'Kelly, 1955; Bree and Cunnane, 1979; Bailey and Bree, 1981). Little is known about the impact of arterial drainage on drought and low flows. The Boyne catchment experienced widespread arterial drainage over the period 1969–1986 (Harrigan *et al*., 2014), with more than 60% of the river network affected. According to Harrigan *et al*. (2014), most works were completed between 1977 and 1979, with works on the main channel of the Boyne completed in 1984. Coincident with arterial drainage, the catchment was also subject to extensive field drainage works. This involved the installation of pipes and ditches to remove surplus water from waterlogged agricultural lands, resulting in shorter transmission times of water to river channels (Harrigan *et al*., 2014). While studies have indicated that field drainage is likely to increase runoff in winter and spring (Burdon, 1986), little work has been completed on the impacts of field drainage on low flows and droughts. Harrigan *et al*. (2014) estimate that more than 30% of the catchment has been subjected to field drainage; however, neither exact figures nor the location of field drainage works are available because of a lack of records on implementation.

3.3 Data and Methods

3.3.1 Meteorological and hydrological data

A monthly catchment average precipitation series was developed for the period 1850–2019. Data from individual stations within the catchment were derived from Met Éireann for the post-1940 period. Hawkins *et al*. (2023) transcribed monthly data from the "10-year rainfall books" held by the UK Met Office. This dataset contains pre-1940 precipitation data for the UK and Ireland. We extracted available data from stations for the Boyne catchment, and, together with available historical data from the Island of Ireland Precipitation network developed by Noone *et al*. (2016), we were able to extend the catchment monthly precipitation series back to 1850. The derived annual series was evaluated for breaks, to identify any inhomogeneities in the series given changing measurement practices and the changing number of stations over time. No significant breaks (at the 0.05 level) were identified (see Figure 3.2).

No long-term temperature series is available within the catchment. We therefore used monthly mean temperatures for Dublin Airport for the period of available records. To extend the temperature data back to 1850, we followed the procedure used by O'Connor *et al*. (2021), whereby gridded monthly mean temperature data from Casty *et al*. (2007) were extracted for grids overlying the catchment and bias corrected using quantile mapping to available observations. The method of Oudin *et al*. (2005) was then used to derive potential evapotranspiration estimates from available temperature records. Daily discharge data for the Boyne catchment at Slane Castle are available from the Office of Public Works for the period 1941–present. Monthly mean discharge data were derived from the available daily data.

3.3.2 Hydrological modelling

We employed a simple lumped conceptual hydrological model to (1) extend monthly river flows to 1850, concurrent with available meteorological data, and (2) reconstruct river flows in the recent record to examine the possible impacts of arterial and field drainage on drought events. We used the GR2M monthly water balance model (Mouelhi *et al*., 2006), which has been used previously for flow reconstruction in Irish catchments (O'Connor *et al*., 2021) and is available via the airGR, a hydrological modelling package using R software (Coron *et al*., 2017). The monthly flow model contains two reservoirs, one representing a soil store and the other a routing reservoir. These reservoirs are governed by two parameters, defining the production store capacity and groundwater exchange coefficient, respectively. The model was calibrated (1942–1959) and validated (1960–1969) using the record for the pre-drainage period and was used to both extend and reconstruct river flows. Given the focus on low flows, calibration and evaluation were undertaken using the log Nash–Sutcliffe objective function. Ten thousand parameter sets were sampled from a uniform distribution representing the range of plausible values for each parameter. Those sets with a log Nash–Sutcliffe score of > 0.8 during the validation period were retained for deriving extended and reconstructed flows. We based our subsequent analysis on the median flows simulated from retained parameter sets.

3.3.3 Standardised drought indices

We employed widely used standardised drought indices to identify droughts in the catchment. Specifically, we used the SPI (McKee *et al*., 1993), the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al*., 2010) and the Standardised Runoff Index (SRI) (Barker *et al*., 2016) derived for accumulation periods ranging from 1 to 24 months. For each index, values between 0.99 and –0.99 are considered near normal, between –1.00 and –1.49 moderate drought, between –1.50 and –1.99 severe drought and less than –2.0 extreme drought. Both the SPI and the SPEI were fitted using a gamma distribution, while the SRI was fitted using the Tweedie distribution, following O'Connor *et al*. (2022). While we typically used the full series as the reference period for fitting distributions, it should be noted that the post-drainage period was used as the reference period when evaluating the impact of arterial and field drainage on standardised drought metrics. Drought events and their characteristics were identified and extracted as follows for each accumulation period. Drought start is defined as the month in which standardised values fall below –1.00, and drought end as when values return to being positive. Drought duration is defined as the number of months from start to end. Drought severity is defined by accumulated deficit, calculated as the sum of deficits during the drought event. We also derived a mean deficit by dividing accumulated deficits for each event by their duration (in months).

3.3.4 Trend analysis

To evaluate changes in standardised indices and drought events, we examined trends using the modified MK test (Yue and Wang, 2004), which employs variance correction to address serial correlation. Trends were evaluated at the 0.05 significance level, with an MK *z*-statistic score of > 1.96 indicating a significant positive trend and a score of < –1.96 indicating a significant negative trend. Trend magnitude was evaluated using the non-parametric Sen's slope estimate.

3.3.5 Assessing sectoral drought impacts

Given the lack of drought impacts formally collated on the catchment scale over the time period of interest, we employed newspaper archives to examine sectoral drought impacts. Newspaper records have been used in analyses of historical droughts in Ireland both to verify occurrence in meteorological records (Noone *et al*., 2017) and to gain insight into societal impacts (Murphy *et al*., 2017; Noone *et al*., 2017). Recently, Jobbová *et al*. (submitted) systematically identified drought impact reports from the Irish Newspaper Archives (https://www.irishnewsarchive.com), a collection containing hundreds of national and local newspapers from across the island. In this work, the authors identified more than 6000 newspaper reports on drought impacts over the period 1733–2019. Each report was categorised according to the drought impact categories and subcategories used as part of the European Drought Impact Report Inventory (Stahl *et al*., 2016). For the period post 1900, the annual number of titles in the archive is relatively stable, with good coverage across the island. We therefore extracted newspaper reports of drought impacts for counties contained in the Boyne catchment from the dataset compiled by Jobbová *et al*. (submitted) for the period 1900–2019. We evaluated drought impacts for the impact categories described in the dataset, namely agriculture and livestock, public water supplies, waterborne transportation, human health and safety, tourism and recreation, terrestrial ecosystems, freshwater ecosystems, freshwater aquaculture and fisheries, and energy and industry.

3.3.6 Linking drought impacts and metrics

Finally, we investigated the relationship between reported drought impacts from newspaper records and standardised drought metrics in the catchment. We focused attention on the SPI and derived correlations between monthly SPI values for accumulation periods of 1–24 months and the annual number of drought impacts reported in the catchment. Linking impacts and metrics in this way can help to inform drought monitoring strategies by identifying the SPI accumulation period and the month most strongly correlated with societal impacts. We focused attention on the most frequently reported impact categories, namely agriculture and livestock and public water supplies.

3.4 Results

3.4.1 Historical droughts in the Boyne catchment

Data rescue activities resulted in the development of a continuous monthly precipitation series for the Boyne catchment for the period 1850–2019. Figure 3.2 shows the annual total precipitation series. Over the 169-year period, we found an increasing trend in annual precipitation that is significant at the 0.05 level. No significant break points were detected in the annual series using the Pettitt change point test. To investigate historical droughts in the catchment, we computed the SPI at 3-, 6- and 12-month accumulation periods. Figure 3.3 shows the resultant SPI series (SPI-3, SPI-6 and SPI-12), with the thresholds for severe and extreme drought noted. Despite the impacts felt in the catchment, the 2018 drought is frequently exceeded in the historical record. Only in the SPI-3 and -6 series does the 2018 event register as an extreme drought (minimum SPI <–2.0).

Using a threshold of –1.00 to indicate onset of a drought, we identified 136 individual events using SPI-3, 83 events using SPI-6 and 42 events using SPI-12. Table 3.1 ranks the top 10 drought events in terms of severity for SPI-3, SPI-6 and SPI-12, using both the accumulated deficit and the mean deficit. The 2018 drought does not feature in the top 10 events for any accumulation period. For accumulated deficits,

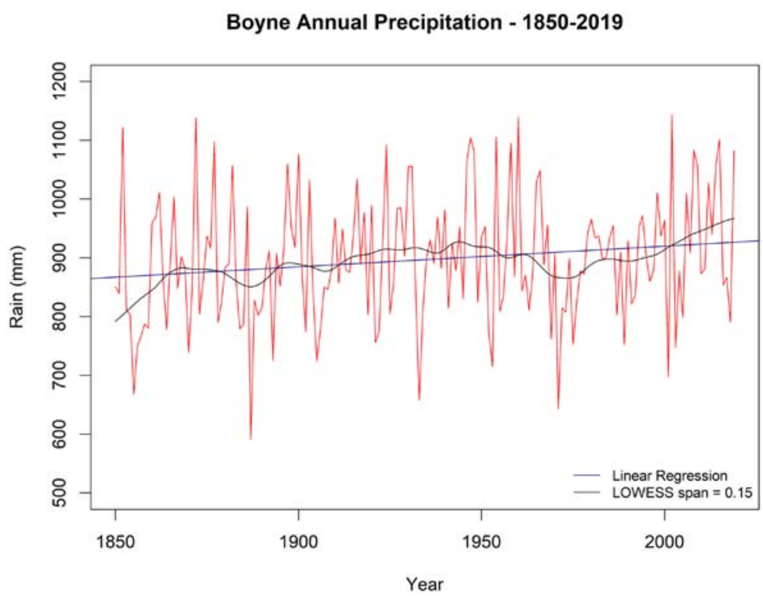

Figure 3.2. Annual total precipitation series for the Boyne catchment for the period 1850–2019.

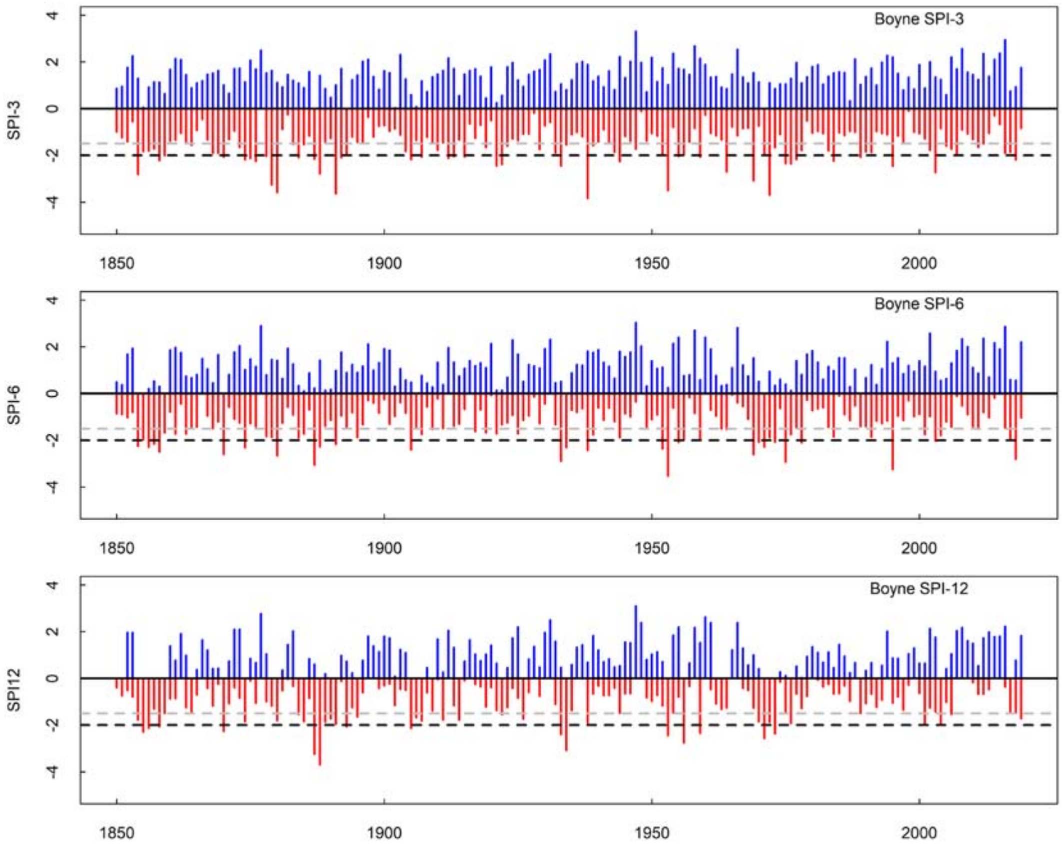

Figure 3.3. SPI series of 3-, 6- and 12-month accumulation periods for the Boyne catchment from 1850 to 2019. Blue lines represent positive SPI values (wetter than average) and red lines represent negative SPI values (drier than average). The grey dotted line represents the threshold for severe drought (–1.5), while the black dotted line represents the threshold for extreme drought (–2.0).

the 1887 drought, which commenced in March 1887 and terminated in April 1888, is the most severe SPI-3 drought in the series. The event also ranks highly in the SPI-6 and SPI-12 series. For both SPI-6 and SPI-12, the drought that commenced in 1854 is the most severe in terms of accumulated deficits in the entire series. Across all accumulation periods, the most recent drought to feature in the top 10 occurred in the early 1970s, while the majority of major events occur prior to the 1940s.

3.4.2 Trends in droughts

We assessed the SPI series for evidence of change in seasonal and annual droughts. The results are presented in Figure 3.4 and Table 3.2. We found increasing trends (less drought) in winter (February SPI-3) and autumn (November SPI-3). No evidence of change was found for spring droughts (May SPI-3). In summer (August SPI-3), we found a decreasing trend (more drought), significant at the 0.10 level. Annual (December SPI-12) and winter half-year (March SPI-6) droughts showed increasing trends (less drought), both significant at the 0.05 level. No evidence of a trend was found in the summer half-year series (September SPI-6). These findings are consistent with those of Vicente-Serrano *et al*. (2021a), who found evidence of decreasing winter and increasing summer meteorological drought in Ireland over the same period (see Chapter 2).

We also tested for trends in the characteristics of the drought events, including duration, accumulated deficits and mean deficits. The only significant trend (at the 0.05 level) found was an increasing trend in accumulated deficits (less severe droughts) from the SPI-3 series (MK *z*-statistic score of 2.02; $p=0.04$).

3.4.3 Arterial drainage and hydrological droughts

Little research has investigated the impact of arterial drainage on droughts. Therefore, we sought to

Table 3.1. Top 10 drought events for each accumulation period (SPI-3, SPI-6 and SPI-12)

SPI	Start date	End date	Accumulated deficit	Start date	End date	Mean deficit
SPI-3	March 1887	April 1888	–21.2	February 1891	May 1891	–2.8
	August 1933	September 1934	–17.3	November 1879	April 1880	–2.2
	February 1971	March 1972	–13.2	November 1922	February 1923	–2.0
	September 1955	August 1956	–13.1	September 1972	January 1973	–2.0
	January 1953	August 1953	–12.7	January 1953	August 1953	–1.8
	December 1873	September 1874	–11.4	April 1975	September 1975	–1.8
	September 1857	April 1858	–11.1	February 1964	April 1964	–1.8
	November 1879	April 1880	–10.9	October 1947	November 1947	–1.7
	May 1995	November 1995	–10.4	May 1995	November 1995	–1.7
	August 1969	February 1970	–10.2	August 1969	February 1970	–1.7
SPI-6	April 1854	September 1856	–29.6	August 1995	December 1995	–2.0
	April 1887	July 1888	–28.7	April 1887	July 1888	–1.9
	August 1933	December 1934	–27.0	October 1969	April 1970	–1.9
	July 1952	November 1953	–21.5	December 1879	July 1880	–1.7
	October 1905	June 1907	–18.5	January 1905	August 1905	–1.7
	August 1869	January 1871	–18.1	August 1933	December 1934	–1.7
	May 1971	May 1972	–16.1	December 1878	June 1879	–1.6
	September 1972	September 1973	–15.5	October 1857	July 1858	–1.6
	October 1857	July 1858	–14.5	February 1874	October 1874	–1.6
	October 1955	August 1956	–14.4	August 1978	December 1978	–1.6
SPI-12	March 1854	June 1860	–93.7	June 1887	February 1889	–1.8
	January 1905	January 1908	–45.1	September 1933	June 1935	–1.8
	September 1971	February 1974	–39.5	December 1952	May 1954	–1.5
	September 1933	June 1935	–38.0	September 1971	February 1974	–1.4
	June 1887	February 1889	–36.3	August 1959	January 1960	–1.3
	June 1889	February 1892	–29.6	January 1905	January 1908	–1.3
	December 1952	May 1954	–26.3	December 1969	November 1970	–1.3
	July 1921	October 1923	–23.0	March 1854	June 1860	–1.2
	July 1975	February 1977	–21.8	January 1874	January 1875	–1.2
	October 1884	July 1886	–21.4	March 1870	July 1871	–1.2

Events are ranked according to accumulated deficit and mean deficit for each drought.

reconstruct monthly river flows for the gauging station at Slane Castle, representing the catchment without drainage. By comparing standardised streamflow indices for the observed and reconstructed series, we aimed to undertake a first investigation of the impacts of drainage on drought in the catchment. The GR2M model was calibrated and validated using the record for the pre-drainage period, before being used to reconstruct the record for the post-drainage period and extend river flow estimates back to 1850, concurrent with available precipitation records. Looking at the time series of reconstructed and observed summer mean flows in Figure 3.5, it is apparent that, overall, the model does reasonably well at capturing flows during dry months, with flows during wet summers (e.g. 2009) being considerably underestimated. Figure 3.5 also indicates possible flow data quality issues in summer months in the pre-drainage period, particularly during the 1950s.

To further investigate the impact of drainage on standardised drought indices, we derived SRI-1, SRI-3, SRI-6 and SRI-12 from observed and reconstructed flow records for the post-drainage period (1980–present). Scatterplots of the derived indices are shown in Figure 3.6. For high flows, reconstructions tend to underestimate the observations for all accumulation periods. This is consistent with arterial drainage increasing peak flows and flows during wet months (see Harrigan *et al*., 2014). Notably,

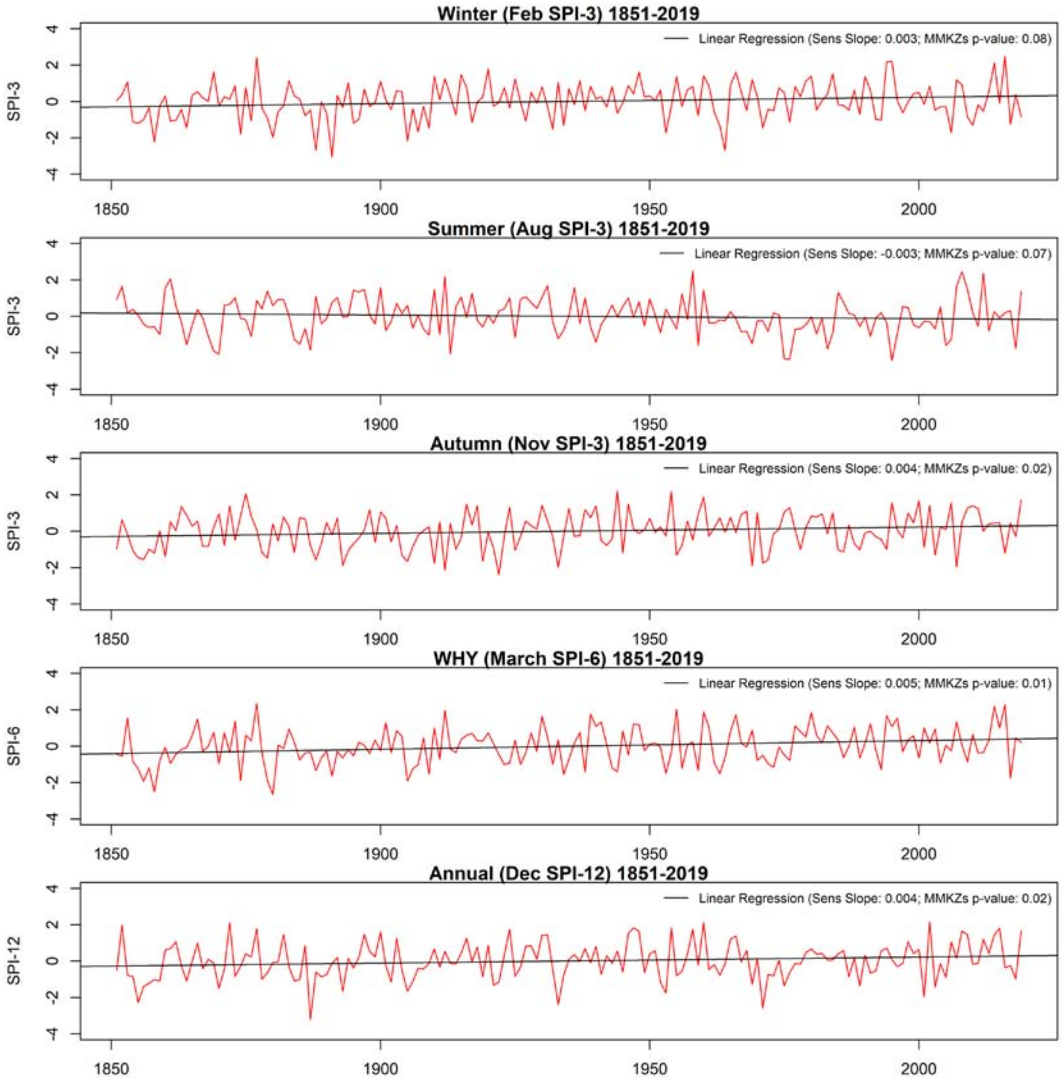

Figure 3.4. Seasonal and annual SPI series used to evaluate evidence of trends using the modified MK test. Each plot shows the observed series together with a linear regression line, Sen's slope estimate, the modified MK test *z*-statistic score and the associated *p*-value for each test.

Table 3.2. Results of trend tests for each indicator of seasonal and annual drought

Indicator	MK*z*-statistic score	Sen's slope estimate	*p*-value
Winter (February SPI-3)	1.74	0.003	0.08
Spring (May SPI-3)	0.71	0.001	0.48
Summer (August SPI-3)	–1.81	–0.003	0.07
Autumn (November SPI-3)	2.35	0.004	0.02
Annual (December SPI-12)	2.42	0.004	0.02
Winter half-year (March SPI-6)	2.75	0.005	0.01
Summer half-year (September SPI-6)	–0.99	–0.001	0.32

Shown are the modified MK test *z*-statistic scores, the magnitude of trend in standardised units using Sen's slope estimate and the associated *p*-value of the test on trend magnitude.

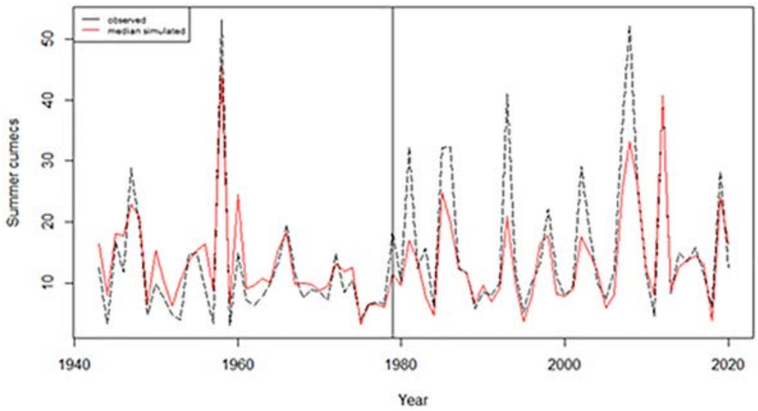

Figure 3.5. Observed (black) and median reconstructed (simulated) (red) summer mean flows for the Boyne catchment at Slane Castle for the period 1941–2019. The vertical black line represents the year in which arterial drainage works were completed in the catchment.

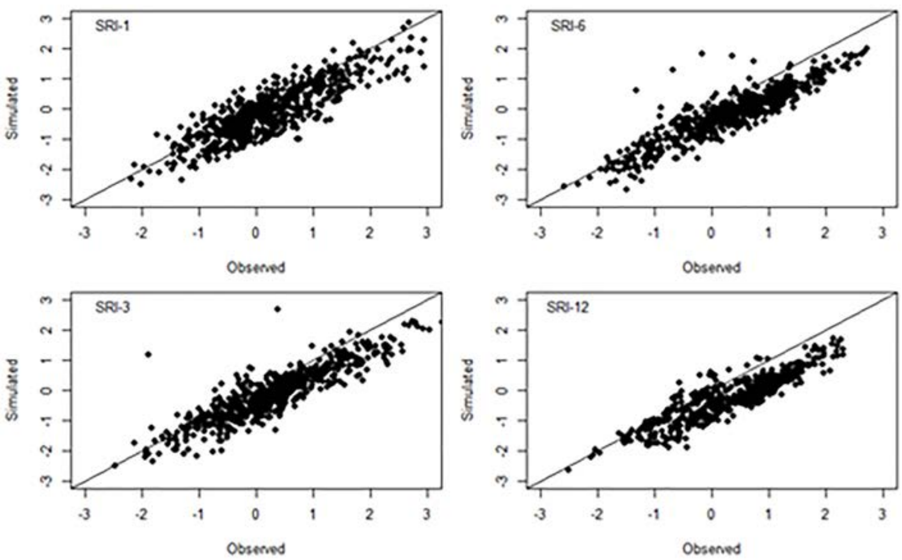

Figure 3.6. Scatterplots of SRI-1, SRI-3, SRI-6 and SRI-12 for observed and reconstructed (simulated) flows for the post-drainage period, 1980–2019.

there is good correspondence between observed and reconstructed low flows, suggesting that arterial drainage has limited impact on droughts.

The impact of drainage on the characteristics of drought events was investigated by identifying drought events for each SRI accumulation period for both observed and modelled flows. Figure 3.7 provides an example using SRI-3 events, as the frequency of these events is greater than that of SRI-12 events. For both accumulated and mean deficits, there is no evidence of significant differences between the pre- and post-drainage periods, using either observed or reconstructed flows. These findings again suggest that arterial drainage has limited impact on the severity of drought events. However, it should be noted that fewer droughts occurred in the post-drainage period. We assume that our reconstructed flows, based on observed precipitation, adequately capture this.

The GR2M model was also used to extend the flow record to 1850, concurrent with available catchment precipitation records. The SRI-3, SRI-6 and SRI-12 series for reconstructed flows for the period 1850–2019 for the Boyne catchment at Slane Castle are presented in Figure 3.8. Based on reconstructed flows, the 2018 drought is categorised as an extreme drought event in all accumulation periods. However, the event

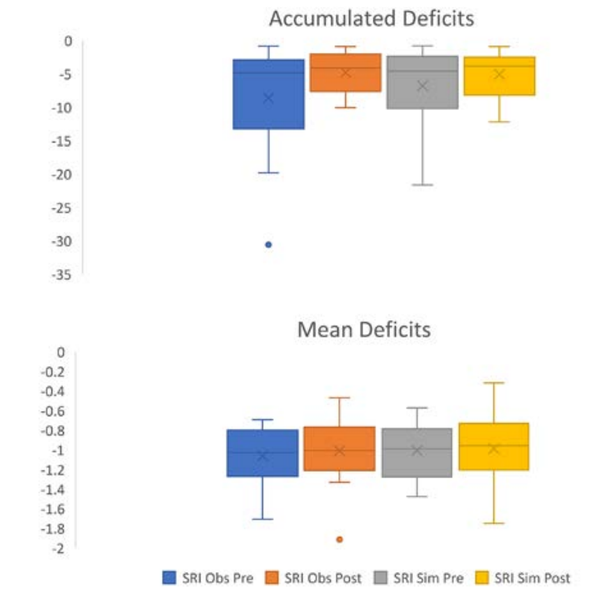

Figure 3.7. Comparison of SRI-3 mean and accumulated deficits from observed pre-drainage (blue) and post-drainage (orange) drought events and reconstructed (simulated) pre-drainage (grey) and post-drainage (yellow) drought events.

is not categorised as being as extreme as other events that occurred in the period of this historical record, particularly for longer accumulation periods (e.g. SRI-12).

3.4.4 Sectoral impacts

Using the newspaper impact database developed by Jobbová *et al*. (2022), we selected drought impact reports from counties contained within the Boyne catchment for the years 1900–2019. In total, we identified 700 individual drought impact reports from this period (see Figure 3.9). On an annual basis, the largest numbers of drought impact reports were found for 1949 (n = 53), 1934 (n = 36), 1921 (n = 33), 1984 (n = 32) and 1989 (n = 22). While 1949 ranks as the year with the largest number of impacts reported, in terms of severity, the droughts of 1949 generally do not rank in the top 10 most severe droughts, as defined by SPI, over the same period. This also applies to droughts in 1984 and 1989. Therefore, while droughts were not extreme in these years, they did result in significant impacts in the catchment. This highlights the challenge of linking drought events and impacts, with the latter largely defined by socio-economic activities and vulnerabilities. Extreme drought events were recorded in 1934 and 1921, with droughts in both years generally ranking in the top 10 events by severity over the past 120 years.

The largest number of drought reports were found for the agriculture and livestock sector. These predominantly relate to problems with grass growth and food production. In total, more than 50% of all

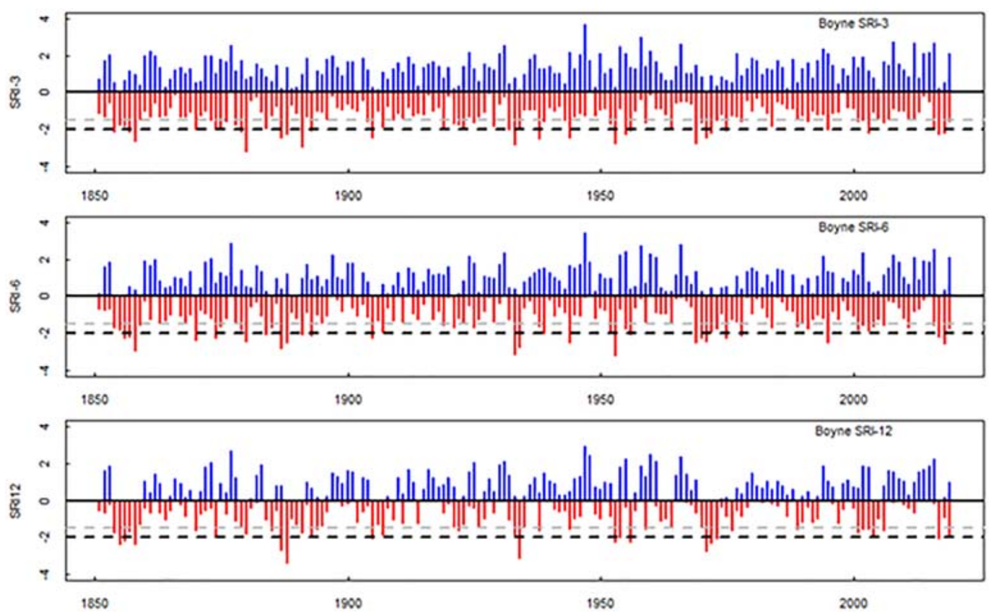

Figure 3.8. SRI-3, SRI-6 and SRI-12 for reconstructed flows covering the period 1850–2019 for the Boyne catchment at Slane Castle. The grey dotted line represents the threshold for severe drought (–1.5), while the black dotted line represents the threshold for extreme drought (–2.0).

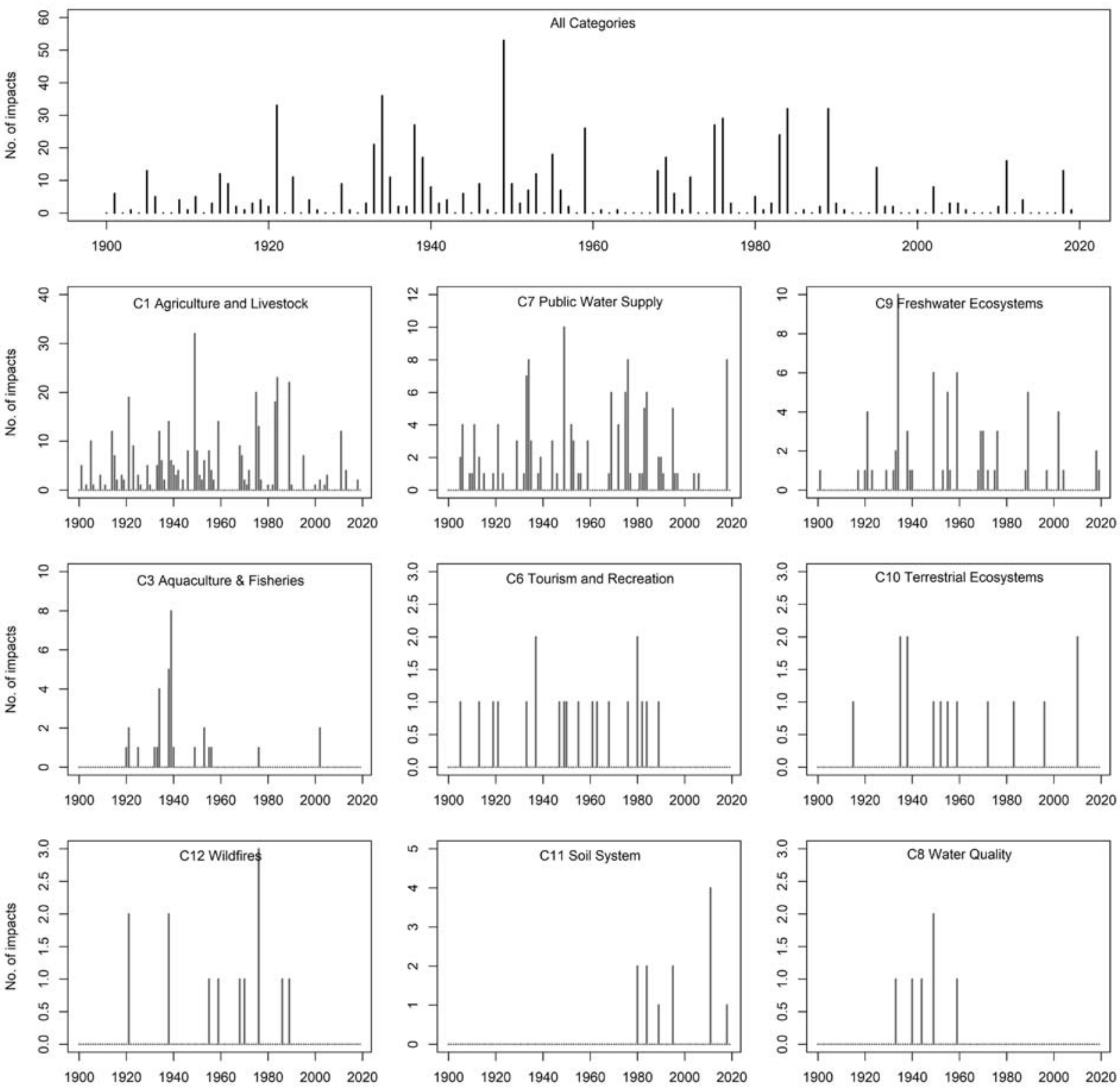

Figure 3.9. Findings from drought impact reports from newspaper archives for the Boyne catchment for the period 1900–2019. The top panel shows the numbers of impact reports for all categories during the period, while the other panels show the numbers of reports for different impact categories/sectors as defined by the European Drought Impact Report Inventory. Note the differing *y*-axis scales.

drought impact reports are associated with agriculture and livestock, consistent with the predominance of this sector in the catchment. The largest numbers of these reports are associated with the droughts of 1949, 1984 and 1989. Figure 3.9 shows an overall decreasing trend in the number of agriculture and livestock impact reports with time. While it is difficult to disentangle exactly why this might be the case, it is likely that a reduction in drought frequency in the post-1970 period, together with the modernisation of Irish agriculture in the 1960s, has contributed to this decline.

The second most commonly affected sector based on findings from the newspaper database is public water supply, with 133 impact reports identified for the catchment over the period of analysis. Numerous droughts over the past 120 years, including in 2018, have given rise to water shortages for major towns in the catchment. Unlike agricultural impacts, which tend to be associated with drought conditions in the spring and summer months, public water supply impacts are often associated with longer drought accumulation periods, with some instances of water shortages associated with drought during winter. For other impact categories/sectors, the numbers of impact reports are considerably smaller. However, the importance of impacts for the freshwater ecosystem and freshwater fisheries should be noted, given the importance of fishing and tourism in the catchment.

3.4.5 Linking drought impacts and accumulation periods

Using the newspaper impact reports and precipitation records, we correlated impacts with SPI accumulation periods ranging from 1 to 24 months, to identify the timing and accumulation period most strongly correlated with impacts. Our analysis was undertaken for the period of concurrent records (1900–2019). Such information could help to inform the development of drought monitoring strategies in the catchment. The results are presented in Figure 3.10. Considering all reported drought impacts, the strongest correlations between drought impacts and metrics are apparent during late summer and early autumn for SPI accumulation periods of 4–7 months. For impacts on agriculture, similar results are evident, with the strongest correlations evident for SPI-4 in July and for SPI-5 in August and September. These results indicate the importance of drought during the spring and summer in terms of its impact on agriculture, which

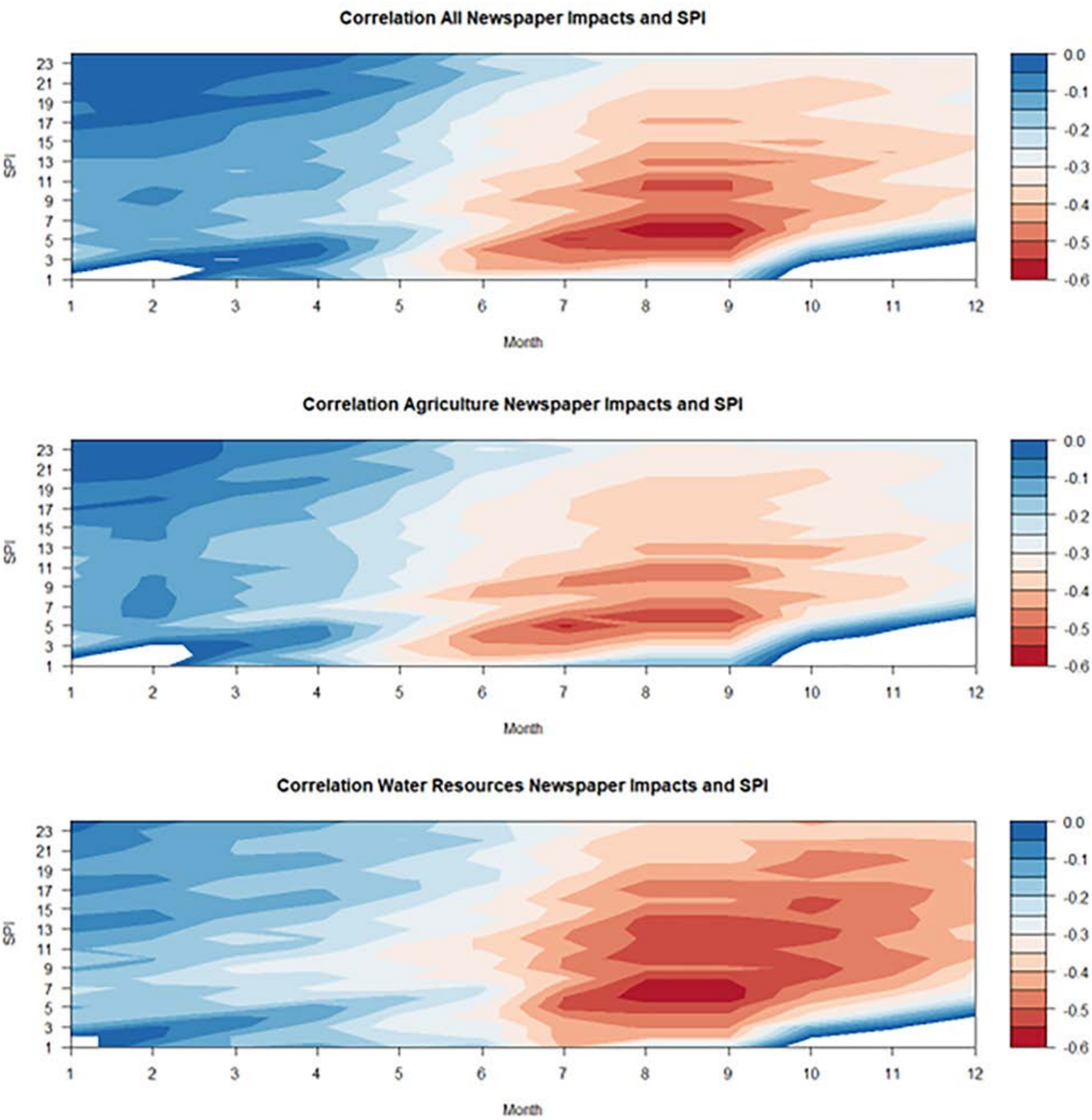

Figure 3.10. Correlations between drought impacts (all impacts: top; agricultural impacts: middle; water resource impacts: bottom) and SPI for accumulation periods ranging from 1 to 24 months in the Boyne catchment for the period 1900–2019.

is based primarily on grass growth. For impacts on water resources, the strongest correlations are evident later in the year and for higher accumulation periods, indicating the importance of prolonged drought conditions for generating water resource impacts. The strongest correlations with water resource impacts are evident for SPI-7 in August and September, indicating the importance of deficits over the late winter to late summer/early autumn period.

3.5 Conclusion

This research has extended available precipitation records for the Boyne catchment to cover the period 1850–2019, providing a detailed view of drought conditions over nearly 170 years in the catchment. Our historical analysis indicates the frequent occurrence of drought in the Boyne catchment and provides a catalogue of drought events derived from the SPI and the SRI. Using standardised indices, we found limited evidence that arterial drainage has affected drought in the Boyne catchment. We also found evidence for trends in SPI series and drought events themselves, dominated by increasing trends in SPI in winter and decreasing trends in SPI-3 in summer (i.e. more frequent summer droughts) over the period of record. We also found an increasing trend in accumulated deficits of SPI-3 droughts, indicating decreasing drought severity. While formal data on drought impacts across sectors are missing in Ireland, we used newspaper archives to gain a better understanding of drought impacts in the catchment. These archives highlight the predominance of impacts on agriculture and livestock, followed by impacts on public water supply. It is not the case that the most severe droughts result in the most severe impacts, with some of the most impactful droughts not being ranked among the most severe events, according to the SPI. This highlights the challenge of tracking drought impacts, even on the catchment scale, using typical drought metrics. For instance, despite the considerable impacts felt in the catchment during the drought of 2018, the event itself does not stand out as remarkable in our long-term reconstructions.

4 Perceptions and Impacts of Drought: Stakeholder Insights and Co-production of Knowledge

4.1 Introduction

Risk perception and reactions to drought are strongly linked to past experiences and memories of events (Taylor *et al.*, 1988; Solano-Hernandez *et al.*, 2020). Given the high likelihood that drought will affect Irish society with greater frequency in the future, there is a need to understand how individuals and sectors perceive and experience drought, to assist in developing tailored coping strategies and in building institutional- and sectoral-level capacity. The CROSSDRO project conducted interviews with individuals and sector representatives affected by drought in the Boyne catchment and nationally, to better understand what drought means for, how it is perceived by and the impacts it has on different stakeholders. We also evaluated barriers to and opportunities for the co-production of knowledge for better drought management.

4.2 Research Design

We followed a mixed-methodological approach, as used in previous studies examining drought perceptions (Dessai and Sims, 2010; Weitkamp *et al.*, 2020). First, an online survey was performed as part of an initial scoping study before interviews were conducted to obtain richer qualitative information. The focus of this study was on individuals either directly affected by or with a professional interest in drought at the Boyne catchment and national levels. A total of 40 semi-structured interviews were conducted between February and July 2021. Interviewees can be broadly divided into three groups: individuals with a direct interest in drought from a livelihood perspective ($n=6$); individuals with a direct interest in drought from a recreational or general perspective ($n=8$); and individuals with an indirect professional interest in drought ($n=24$). Most of our interviewees with a professional interest work for state organisations or agencies operating at the national level ($n=26$). All interviews were conducted remotely via telephone, Zoom or a similar virtual meeting platform. Interviews ranged from 30 to 100 minutes in duration and were conducted by the same interviewer. Interview questions sought to examine drought vulnerabilites and understandings, past drought experiences and coping strategies, and concerns around future drought risk. Semi-structured interview protocols were tailored to each interviewee depending on the type and scale of their interest. Interviews were recorded and transcribed. A thematic analysis was conducted to identify and code key themes from the interviews. The first round of coding identified specific drought events reported by each interviewee, commonalities and differences in how drought was discussed and understood, and interviewees' specific connections to drought impacts. Analytical coding was then performed, where additional patterns and categories were identified through an inductive and interpretation exercise (Bryman, 2008).

4.3 Results

We report the commonalities and differences in interviewees' experiences of drought, future concerns and potential coping strategies. To protect interviewees' identities, names are replaced by codes. Most interviewees (32/40) reported some kind of experience, memory or knowledge of historical drought events in Ireland. In terms of specific droughts, the droughts of summer 2018 and spring 2020 were most frequently mentioned. Some interviewees also referred to memorable droughts in the 1950s and 1970s, and the hot and dry summers of 1995, 2006 and 2013. The most frequently identified drought-related experiences or concerns related to impacts on rivers and waterways (18/40), water management (15/40) and dairy farming (10/40). Interviewees across the sample commented on increased climate variability and more frequent extreme weather in Ireland in recent years:

> I have noticed in the last 10 years things are getting more erratic. Erratic in winter as well as summer. (Interviewee A from Waterways Ireland)

> Over the past 4 or 5 years, you can't go by the calendar any more. (Interviewee from Coillte)
>
> [We have seen] a regime shift in terms of climate … you are looking at two completely different worlds. (Interviewee from Atlantic Salmon Trust)

For the remainder of this chapter, interviewee responses are grouped based on four primary drought perspectives identified by interview analysis: agriculture and forestry, water management and navigation, environment, and river and recreational use.

4.3.1 Agriculture and forestry

This group of interviewees was composed of local-level farmers, growers and producers in the Boyne catchment, and national-level scientific and governmental stakeholders from the agriculture, forestry and peat sectors. In terms of historical drought events in Ireland, the 1970s, 1995, 2018 and 2020 were the most frequently mentioned, with 13 out of 15 interviewees directly referencing impacts from the summer of 2018:

> There have obviously been a few events in the last 10 years but the very first one I remember is 1995 … that really went on, it felt like it went on forever. I remember the [Boyne] river being really low, being able to walk over it. And people … hadn't really experienced anything like that for a long time. People [have also said] there was one in the 70s. (Interviewee from a rapeseed oil producer in Co. Meath)
>
> [2018] was the first time for such a long drought. The previous drought before that was '95 ... There have been many droughts but when you talk to a farmer it's '95 and 2018. (Interviewee from Irish Farmers' Association/dairy farmer)

While drought was generally considered to go hand in hand with hot weather, one farmer also recalled a cold drought event in spring, several years ago:

> There's been cold droughts … very long periods of cold weather … easterly winds, that blocking event that they are talking about, sudden stratospheric block … you don't get any rainfall. Next thing, you're worried about your water, but it's cold and it's not the idea of a drought that we all have. (Interviewee from a rapeseed oil producer in Co. Meath)

The most frequently identified drought-related experiences or concerns related to dairy farming (8/15), income (6/15), water management (5/15), horticulture and crop production (5/15), and forestry (3/15). Local-level stakeholders were primarily concerned with the impact of prolonged dry weather on their land and the effect that this might have on their livelihoods (7/8), while national-level stakeholders were more concerned with the broader impacts on the agri-food sector in Ireland (5/8). Among the agricultural drought impacts identified, the most frequently mentioned were those related to grass growth, fodder management and water availability for dairy farming. Interviews with farmers and members of Teagasc, the Irish Farmers' Association (IFA) and the Department of Agriculture, Food and the Marine (DAFM) indicated that dairy production is particularly at risk from drought in the Boyne catchment and nationwide. According to a dairy farmer, drought is synonymous with poor grass growth over a 21-day period and shortages of crops for fodder and bedding:

> When your 21-day rotation doesn't replenish you with grass ... your grass isn't being replenished on the standard rotation length and that means then farmers have to go in with buffer feeding and concentrate feeding, which is more expensive. (Interviewee from the IFA/dairy farmer)

Interviewees reported that grass growth dropped dramatically in 2018, particularly on free-draining soils and well-drained catchments in south-eastern counties. This had implications for the availability and cost of feed and bedding materials for livestock, and ultimately milk production:

> In 2018, grass would have been very, very severely stunted. (Interviewee C from DAFM)
>
> People on dry sandy soils. They ran out of grass. (Interviewee A from DAFM)

> You would hear of lads having to reduce their stock because they couldn't feed their animals and that's not sustainable. (Interviewee B from DAFM)
>
> In times like that sometimes straw would be fed just as a feed to keep animals ticking over. Even in that year there was a shortage of straw. (Interviewee C from DAFM)

A grassland scientist from Teagasc summarised the acute nature of drought impacts on dairy farming as follows:

> The practical consequence of drought for a farmer is how do you get through that period when the forage crashes. Because once the rain comes back, the grassland growth will recover real quick. But how do you get through that hungry period? (Interviewee from Teagasc)

Several interviewees mentioned that the extremely wet calendar year and cold spring preceding the 2018 summer drought extended the winter livestock housing period and exacerbated the fodder crisis. Some interviewees reported how unprepared the dairy sector in Ireland had been during this event. Farms with large herds, operating at maximum capacity, were considered particularly vulnerable to climate extremes:

> We had pretty significant issues, particularly in the really intensive large dairy herds … To find feed for 50 or 60 cows, that's kind of doable, but for 600 cows now you have to buy silage bales in large volumes … you're very dependent on the market. (Interviewee A from DAFM)
>
> Since 2015 there's [been] huge dairy expansion and … everyone was pushing out to the maximum and trying to maximise the stocking rate and not really considering how the climate could actually jeopardise the systems and that came to the fore in 2018. (Interviewee B from DAFM)

Several interviewees were also concerned about the potential impact of water shortages on animal welfare and farmer wellbeing. Dairy production is very water intensive, particularly in the summer months. Dairy cows require up to 70 litres of water a day, and additional water is required for the milk production process and the cleaning of equipment and buildings. Water shortages impact the behaviour and welfare of livestock, as well as the wellbeing of farmers:

> If you don't have enough water and enough trough space you tend to get aggression and dominance issues, which are also welfare challenges. (Interviewee A from DAFM)
>
> When you have cows looking for water or feed … any farmer will tell you, that's more stressful than anything. (Interviewee from the IFA/dairy farmer)

Many farms rely on private or community-owned group schemes for their water supply. According to an interviewee from the National Federation of Group Water Schemes (NFGWS), the 2018 summer event alerted farmers to the potential vulnerability of their group water schemes and private wells:

> We would have had issues pre-2018 obviously, but not to the same extent, and I think that kind of opened our eyes and we … probably were a little bit unprepared. (Interviewee from the NFGWS)

During both the 2018 and 2020 droughts, water demand across all schemes increased by 20–30%. This meant that in some places demand was greater than the volume of water that could be pumped and processed by treatment plants. As a result, many rural water users were concerned that their supplies were close to running dry:

> Water levels in the source reduce or go down very slowly and do not recover to the same extent that they would normally do. Obviously, panic can set in at that stage. (Interviewee from the NFGWS)

In terms of adaptation or strategies to cope with future drought, the dairy farmers interviewed highlighted the importance of fodder management and access to affordable imported feed when required. They also suggested various approaches to improve the resilience of their water supply, including investment in irrigation equipment, conserving water and accessing more water from either rivers or new wells. According to one farmer, the commercial damage caused by the 2018 drought has had a significant impact on dairy farmers' attitudes to drought risk in Ireland:

> Farmers have become more aware of drought [since 2018]. They plan for more buffer feeding and more of a reserve, so instead of having a 6-week reserve they have a 3-month reserve. (Interviewee from the IFA/dairy farmer)

This interviewee also suggested that Irish dairy farmers are open to new practices or technology that might increase resilience to drought:

> We're very receptive to advice and as advice changes … Before you would have never measured grass. You would have just followed your rotation and never thought anything more. Now farmers are walking their farm once a week, measuring their grass twice a week during periods of high growth. (Interviewee from the IFA/dairy farmer)

Interviewees from national-level scientific and governmental agencies stressed the importance of EU-level financial support during drought events and the potential need for "weather insurance" in the future, so that dairy farmers can be compensated for drought-related losses. A senior official from DAFM also stressed the importance of engaging the farming community about drought:

> [It is] only a matter of time before there is an investment of insurance premium into the protection of the grassland resource. (Interviewee from Teagasc)
>
> It's also about communicating in some way to farmers that this is a risk that you have to consider ... dairy cows drink maybe between 40 and 70 litres a day depending on how high yielding they are. If you have 500 or 600 cows, that's a lot of water. (Interviewee A from DAFM)

This interviewee also suggested that grasslands made up of a mixture of different species could improve drought resilience. Referring to sectoral- or national-level planning, they also expressed alarm at the apparent lack of awareness shown by farming leaders of any strategic planning for drought going on during a recent public event on drought:

> [Somebody] asked a question at the end … about how well prepared they think the industry is to face these kinds of pressures in the future. And there was a complete silence from the whole panel. And it was really a clear conclusion that nobody is prepared. There are short-term emergency responses to try and muddle through as best as possible. But there is no plan, nobody has a plan, nobody is thinking about this on a systematic basis and that's really worrying. (Interviewee A from DAFM)

According to farmers and DAFM staff, the prolonged dry weather in summer 2018 and spring 2020 also affected crop production in terms of yield and quality (e.g. potato, oilseed rape, oats, straw and grain). The most severely affected farms were in the south-east of the country, where free-draining and heavily tilled soils struggle to retain enough moisture. According to an interviewee from the DAFM climate adaptation team, a focus on continuous cereals in recent years (e.g. oats, wheat, barley, malt) has damaged the soil structure and reduced climate resilience on these farms:

> Soil is massively important for [increasing] resilience to climate and if your soils are completely drying out because maybe they have been over tilled for decades … there's no structure to that soil. You are changing that whole land–water dynamic so if the soil is all broken up it's dry and you're exposing it to erosion from wind and rain. (Interviewee B from DAFM)

According to a tillage inspector at DAFM, irrigation has become more necessary in recent years, particularly for potato farmers in the south-east of the country. Interviewees also raised concerns about the emergence of new diseases, pests and weeds as drought events become more frequent:

> A lot of potato farmers are already irrigating … Back to 2018 … guys would have been spending large amounts of money on pumps

> and irrigation systems to make sure that they fulfil their contracts. (Interviewee C from DAFM)
>
> As we experience more droughts, crop diseases are going to move from wet weather diseases to dry weather diseases. New pests and weeds too. We don't have experience of those. (Interviewee C from DAFM)

In terms of adaptation or strategies to cope with future drought, this interviewee suggested that Irish tillage farmers should try to diversify, and move away from traditional commodity crops (e.g. malt and barley), to not only build commercial resilience to extreme events but also enhance soil quality and moisture content. Several interviewees also emphasised the potential role of the state advisory service (Teagasc) and the importance of farmer-to-farmer learning for awareness raising and knowledge exchange.

The forest sector also reported significant impacts on newly planted forests in 2018. An inspector from the Forest Service who visited sites during the summer of 2018 reported severe stress and 100% failure on some sites for the first time in his career:

> I have a few sites in my mind … they would have been planted in native woodland in February/March and went out in July/August and there were no trees. They were all gone. 100% failure of trees and I have never come across anything like that. That was the first time we had come across it. (Interviewee from the Forest Service)

DAFM set up a financial support scheme so that landowners and foresters could replant young trees that had failed. According to a private consultant from Purser Tarleton Russell Ltd (PTR Forest), young broadleaf forests planted in free-draining mineral soil were particularly susceptible:

> Sites all across the south-east were just withering away and dying, and the mortalities were excessive across sites. (Interviewee from PTR Forest)

A manager from Coillte reported how prolonged dry spells have inhibited growth on his tree nursery. Irrigation is seen as helpful tool, but cannot be relied on as a substitute for regular rainfall:

> The irrigation will keep things alive … but it's no real substitute ... A good drop of rain is far better than any irrigation system. Again, it's a tool we need, we have to have it because we can't rely on the weather to get rain and moisture at the time of sowing. (Interviewee from Coillte/nursery manager)

In terms of adaptation or strategies to cope with future drought, all interviewees from the forest sector suggested that foresters need to diversify planting, while considering species and provenances that can withstand more extreme climates and the resulting changes in pests and diseases:

> We need ... mixed species in the future and planting the right tree in the right place, moving away from this Sitka spruce planted everywhere because it's the quickest return on your investment. (Interviewee from PTR Forest)

4.3.2 Water management and navigation

This group of interviewees was principally composed of scientists and engineers working for governmental organisations and civil society organisations operating on a national scale. In terms of historical drought in Ireland, the summer of 2018 was by far the most frequently reported event (8/12 interviewees). The most frequently identified drought-related experiences or concerns related to water supply and wastewater management (8/12), and streamflow and water quality in rivers (5/12). Governmental actors were concerned with the impact of prolonged dry periods on rivers and water resources, while civil society organisations were more concerned about the impact of drought on public and community-owned water supplies. Regarding impacts on rivers, several governmental actors mentioned how low flows reduced water quality, as they reduce the extent to which pollutants are diluted and the river's ability to assimilate wastewater:

> … where you are discharging wastewater into a stream or river that now has less capacity because there is less water in it … your

> impact … may be more. (Interviewee from the Department of Housing, Local Government and Heritage)
>
> The ability of our rivers to have enough flow in them to maintain their ability to assimilate the wastewater … is really, really important and the Liffey and the Boyne are good examples of that. (Interviewee from the EPA/EPA scientist)
>
> Higher nutrient content combined with the low flow … exacerbates everything. (Interviewee from the Local Authority Waters Programme)

Several interviewees also remarked that often, when there is heavy rainfall after a dry spell, as was the case in the summer of 2018, recently applied agricultural fertiliser and wastewater solids that build up in pipes are flushed into river systems:

> The assimilation capacity just wasn't in the rivers … you get build-up of silt and solids and grease and all the rest of it in pipes. And when rain comes, it flushes it all out. (Interviewee from Climate Action Regional Office)

An EPA scientist also explained how during dry periods authorities are constantly having to abstract water for domestic water and navigation, while also maintaining the water level for wastewater management and water quality:

> When you get droughts you have to keep abstracting your water for domestic water supply. So you end up pumping water because the water has fallen below the outtake level, and you absolutely have to do that, but you also have to maintain the water in the river to sustain the ecology and to dilute the wastewater, and there's also a navigation abstraction on the Liffey at the Leinster Aqueduct and at the Boyne at the Boyne Aqueduct, Irish Water take water for the Royal Canal or Waterways Ireland. So you are spinning plates in that situation where you are trying to balance what you take out and leave enough that it will safely dilute what's put back in. (Interviewee from the EPA/EPA scientist)

Interviews with officials from the Department of Housing, Local Government and Heritage (DHLGH) and others with an understanding of public water supplies suggest that, while there has been broad agreement on systemic problems with Ireland's supply network for a long time, the 2018 and 2020 drought events were a wake-up call for the public water supply sector. Interviewees reported concern about the sustainability of existing supply infrastructure and how recent events had brought home our vulnerabilities and focused minds within the DHLGH. Unsurprisingly, Dublin was considered particularly at risk due to the lack of storage capacity and increasing demand:

> … the experience of 2018 and 2020 ... has brought home to us here in Ireland the vulnerabilities that we have that maybe weren't so front and centre and I guess the frequency of two such severe droughts so close together has really focused minds. (Interviewee from the DHLGH)
>
> … if we haven't had any rain for 3 or 4 weeks after March ... in an Irish context there's so little storage in the ground that hydrological droughts can happen really, really quickly. (Interviewee from the EPA/EPA scientist)
>
> Well I suppose the most immediate risk is in supplies like Dublin City where you have very, very little headroom. So you are operating on a 2–3% headroom. International practice would be nearer to 15% or 20%. (Interviewee from the DHLGH)

Several stakeholders highlighted how supplies that rely on flashy catchments in the west can also be vulnerable, even during short dry spells like the one in 2020:

> In the south-west of the country, we have a lot of run of the river supplies which are very vulnerable to this type of situation where the river drops. [In 2020] the river needed to be sandbagged and you can just get the pipe to be able to extract the water out of it. In some very small supplies, we were tankering the water in ... So we had a hosepipe ban put in place, so it was a difficult enough situation and fairly touch and go at times. We were reducing the pressure during the night and

> turning off certain areas. (Interviewee from the DHLGH)

Multi-year events were also highlighted, as some reservoirs and aquifers need time to recharge. In terms of the Boyne catchment, public water supplies did not seem to be an immediate concern, but general concerns were raised that development of the Dublin–Belfast economic corridor could bring pressures in the long term.

In terms of adaptation or strategies to cope with future drought, several interviewees suggested a mixture of demand management, engineering-based solutions (e.g. water transfers, reservoirs, repairing leaky infrastructure, groundwater exploitation) and nature-based solutions (e.g. peatland restoration and natural water retention measures). An interviewee from the EPA highlighted how challenging it is to engage politicians and the public on water management issues in Ireland in the context of larger-scale crises such as COVID-19 and climate mitigation actions:

> Communicating effectively and actually achieving resonance with policymakers and the wider public on the importance of [drought] is a problem … First of all, you have to win the argument that it's worth doing something about ... The engineering solutions are there and in a stepwise way you can do several things depending on how bad the situation gets … Winning the society argument is the key ... Climate action is the big fish in the pond at the moment. If we don't get that right, what we're doing with rivers is only gardening really. We have to sort that out. We have to convey to people very effectively, and it's not easy to do, that these things are all mutually supportive ... what we do in terms of adaptation has to support mitigation and vice versa. (Interviewee from the EPA/EPA scientist)

An interviewee from the DHLGH also commented that the main challenge for water planners when calculating future water supply scenarios is "settling on a common picture … prediction of the future" (Interviewee from the DHLGH). Despite not being mentioned by other interviewees in the water management group, two interviewees from Waterways Ireland (WI) highlighted the impact of dry weather and water shortages on Ireland's network of inland navigable waterways. They seemed to define drought in terms of having access to enough water so that the waterways can function from both a navigational and an ecological perspective:

> Our canals run on water; water is the key element here. There isn't an ecology without water … often at times in an organisation like ours … we fail sometimes to see the water … There's only so much of the pie and with climate change our concern particularly with regard to drought is that the pie is shrinking … I think the right amount of water is incredibly important to us in the canals and we already have issues with drought. (Interviewee B from WI)

Without a reliable supply of water, WI may not be able to maintain waterway levels, which has consequences for navigation, recreation and ecosystem health. The WI interviewees described how, as the water levels drop, more light reaches the canal bed, resulting in weed growth. A combination of shallow water, limited boat traffic and weed growth can prevent WI's machinery from clearing weeds and maintaining the functionality of the waterway infrastructure:

> Weed growth is massive because we can't get our machines to work on the level of water in the canal, so that means the weeds start to grow [further]. (Interviewee A from WI)
>
> Managing that weed is important for the ecological interest as well. It's not just so our boats can go down there. (Interviewee B from WI)

Interviewee A also reported concerns about the structural integrity of canal embankments and bridges as water levels drop and they dry out and crack:

> My embankments are cracking in the dry and then when they become saturated that crack becomes a flow for water to leak. (Interviewee A from WI)

The Royal Canal, which cuts across the country from the Midlands to Dublin and is fed by the Inny catchment/Lough Owel, also supplies the town of

Mullingar (Co. Westmeath). Interviewees suggested that this supply is becoming less and less reliable as Mullingar grows and we experience more frequent and longer periods of dry weather:

> In 2017 … we had such dry weather in the Inny catchment, that our levels are down maybe 600 mm. They are impassable. (Interviewee A from WI)
>
> We are already under pressure with regard to getting water for our canals. Significant pressure. We have it every year. (Interviewee B from WI)

During prolonged dry periods in recent years, WI has regularly had to divert water from the River Boyne to maintain a navigable level on the Royal Canal:

> We're pumping water out of the Inny and the Boyne and that's not sustainable in the long term. (Interviewee A from WI)

In terms of adaptation or strategies to cope with future drought, WI engineers plan to reduce water leakage from their canals and try to curtail weed growth by using machinery to muddy the water during dry periods.

4.3.3 Environment

This group of interviewees was composed of ecological scientists, policy actors and local biodiversity champions in the Boyne catchment. Five out of seven interviewees directly referenced a specific period of drought, with the 2018 drought being the most frequently reported. Within this group, the scientists and local champions all identified drought-related experiences or concerns related to peatland ecology (5/7), wildfires on peatlands (5/7) and wildlife (5/7). The policy actors were more concerned with the broader discourse around climate change and the environment. Interviewees concerned about peatland health highlighted that extended periods of dry weather are likely to further destabilise and degrade wetlands and peatlands that already have limited resilience:

> Drought will ... increase the degradation I would say but also make it more difficult to restore [peatlands]. (Interviewee from an Irish university)
>
> All those systems are really badly drained, they are badly damaged. So there is no water in the system, so you are depending on a constant supply of rain to even have areas that are relatively intact, in anything like good condition. So the problem we have now is [with] more frequent periods of drought, it's going to be harder to restore these systems. (Interviewee from the National Parks & Wildlife Service)

Several interviewees observed surface drying and cracking during the 2018 drought, attributing this to an absence of the moss or algae layer that would be found on healthy peatlands:

> In 2018 … [bogs] I have never seen dry were suddenly dry … You could walk across [the bog] in sandals and you see the cracking of the peat and the drying out and the crumbling. (Interviewee from an Irish university)
>
> I was very struck by how dry the planted bog vegetation was. It was almost like the bog had lifted off the surface of the mountain so to speak. And I was walking over it and it was like parchment paper, I was breaking through it, breaking through the vegetation, it was almost like the vegetation had peeled away from the peat below. And obviously that's because things had dried out to such a degree that it had lost that kind of resilience. (Interviewee from Bord na Móna)

In the past, the state company responsible for harvesting turf from the bogs (Bord na Móna) welcomed dry weather, as it increased productivity. However, as the company moves towards a policy of restoration or rehabilitation, interviewees reported that it is going to need to manage water levels carefully, which will be challenging as droughts become more frequent and demand for water resources increases. Several interviewees were concerned about fires starting on drained, harvested peatlands during periods of prolonged dry weather:

> Because the peat is dry and it's dry everywhere, you set it off and it starts

> spreading. (Interviewee from the National Parks & Wildlife Service)

One interviewee also suggested that compound extreme events (i.e. dry weather followed by intense rainfall) are also likely to create conditions for more serious bogslides in Ireland, which, in addition to the ecological damage, can impact on local property, water quality and biodiversity downstream. Some interviewees also highlighted the impact of drought on wildlife. Dry conditions and resulting fires can have short-term effects on insect and bird populations. Some aquatic birds, the freshwater pearl mussel and natterjack toads were highlighted as species that can be very sensitive to reductions in surface water levels. However, an interviewee from the National Parks & Wildlife Service argued for drought to be defined according to the specific ecological context:

> Drought needs to be defined as well, because that will differ between different habitats … you've got to contextualise it for its own particular environment … drought is relative, 1 month of very low or no rainfall in the west can be detrimental to something like a freshwater pearl mussel. (Interviewee from the National Parks & Wildlife Service)

In terms of adaptation or strategies to cope with future drought, all three of the professional ecologists in this group suggested that restoration and rewetting of peatlands may improve future resilience. However, they highlighted that this approach will not be effective in every case, and that the potential restorative benefits should be carefully weighed up against the potential impacts of such interventions on local livelihoods and communities.

4.3.4 River and recreational use

This group of interviewees was principally composed of anglers and boaters from the Boyne catchment. Five out of six interviewees directly referenced a specific period of drought, with the 2018 drought being the most frequently reported. Within this group, the most frequently identified drought-related experiences or concerns related to the effect of low water levels on river fish health and angling (3/6) and navigation (3/6). Anglers expressed concerns about the impact of low flows on fish habitats, movement and health, while boaters were principally concerned about the impact of low levels and subsequent weed growth on navigation and the general aesthetic of rivers and waterways. From an angling or fisheries perspective, drought was frequently mentioned as a contributor to fish stress and kills due to the compound effect of low flows, increased water temperatures, low oxygen levels, poor water quality, weed growth and increased predation:

> This combination between the low flow, high temperature and the oxygen to me is really very, very worrying at this stage. (Interviewee from the Atlantic Salmon Trust)

All anglers reported a drop in river levels and impacts on fisheries during the summer of 2018 and spring of 2020. They reported that, during the summer of 2018, salmon movement and health was so badly affected on some rivers that anglers voluntarily stopped fishing until conditions improved:

> Inland Fisheries Ireland actually issued press releases telling people to stop fishing, that these temperatures have never been seen before. (Interviewee from the Atlantic Salmon Trust)
>
> The fishing was cancelled pretty much for the whole summer because the river was too low and they were worried about stress on fish. (Interviewee B from Navan Anglers, Co. Meath)

According to one angler, the impacts of the drought in the spring of 2020 would have been as serious as those in 2018 if it had lasted any longer:

> We had a similar event in April [2020] … another 2 more weeks of that and we were in serious bother … it was earlier in the year and that's what saved it … if it had occurred a few months later [the impacts on fish] it probably would have been every bit as bad as 2018. (Interviewee from Kells Anglers, Co. Meath)

Another angler mentioned that there were far more serious impacts on the River Boyne and its fisheries in the 1950s:

> As bad as things were a couple of years ago, they weren't that bad! … I just came across pictures of it recently and I just went wow! We thought that what we saw a couple of years ago was unprecedented but it wasn't … 1958 if my memory serves me right. (Interviewee A from Navan Anglers, Co. Meath)

One interviewee was able to provide a national perspective on drought and fisheries. They had observed climate regimes in very flashy catchments in the west of Ireland change from almost daily "soft rain" events to more frequent flood and drought events, leading to drops in the numbers of fish and other wildlife:

> We were seeing effects in terms of the [fish] productivity of these streams and also my colleagues have been looking at it in terms of the invertebrates. (Interviewee from the Atlantic Salmon Trust)

They also highlighted the difference between these catchments and the Boyne catchment when thinking about the potential impact of dry weather on low flows:

> The water [in flashy mountain catchments] runs off very quickly and so it's very different to the Boyne even though the Boyne is destroyed by drainage. At the same time, it still has a capacity to retain water. Whereas, in those particular systems, there is nothing to retain the water except lakes and you really do see the effects very quickly in terms of the streams being denuded of water. (Interviewee from the Atlantic Salmon Trust)

In terms of adaptation or strategies to cope with future drought, one angler stressed the importance of effective abstraction regulation and enforcement:

> Farmers were blocking up streams to impound them so they could suck water out ... and then the next fellow doing the same … and the next fellow … absolutely no consequences. The only law that comes into effect is when the river runs dry. (Interviewee from Kells Anglers, Co. Meath)

Another angler suggested engaging and incentivising the farming community with catchment and peatland restoration as a way to reverse decades of drainage policies:

> … why don't we make the farmers into water stewards and that's what my training is about at the moment. We are taking young farmers and we're trying to get them to understand the value of the liquid that they have on their farm in terms of water and how they can manage it to their benefit. We as a community should be supporting them to have wet fields and supporting them to have wetlands and to recreate their bogs and that's the only way it's going to work because these people are trying to make an income out of it. (Interviewee from the Atlantic Salmon Trust)

From a boating perspective, the effect of low flows on navigation was also highlighted as a potential concern during interviews with members of the Heritage Boat Association, a canoe club on the Royal Canal (Co. Meath) and a boating tour company in the lower part of the River Boyne:

> If the [canal] levels are low you cannot navigate. Simple as that … as the water goes down you hit the edges [of the boat] very quickly. (Interviewee from Heritage Boat Association)
>
> If the river is very low your boat is just going to be scraping off stones and it's not going to be much fun, you know what I mean. So there's a danger … if the river levels aren't right. (Interviewee from a canoe club on the Royal Canal, Co. Meath)

Boaters also reported how low water levels can encourage weed growth, which has knock-on effects on navigation and the aesthetic value of the waterways:

> Low levels to us would be weed growth because the shallower the water, the more weed that grows so certainly that would be

an issue. (Interviewee from Heritage Boat Association)

The effect of the drought conditions is the build up of weeds because of heat. That's the big thing for me … When you get it right and it's crystal clear and … maybe 6 or 7 feet deep … you can actually see fish swimming around you. (Interviewee from a boating tour company)

4.4 Insights from Interviews

This research sought to better understand drought perceptions and impacts across different sectors and key vulnerabilities, to better prepare for drought in future. Most reflections on drought among the interviewees were drawn from the 2018 drought, with very few interviewees able to draw on impacts and responses from earlier droughts. As indicated in Chapter 3, the 2018 drought, while significant, is not remarkable in the long-term record. More intense, longer-lasting droughts have occurred within living memory, and it is important to draw out impacts and responses from those events. Some interviewees also referred to the dry summers of 1995, 2006 and 2013, even though they are perhaps remembered more as heatwaves. This would support findings from the UK that drought is usually associated with warm and sunny weather during the summer. Having said that, those more dependent on and aware of weather conditions (e.g. farmers) did highlight concerns around dry spells in winter and early spring under cloudy and cold conditions (known as grey or cold droughts).

Very different perspectives of drought impacts were provided across sectors, indicating the challenge of one-size-fits-all approaches to managing drought. Stakeholders from the dairy sector reported that grass growth dropped dramatically in 2018, particularly in Munster and Leinster. They talked of "unfamiliar territory" and "a sector unprepared for such a long drought" as silage and straw prices "went through the roof". Similar conditions across Europe led to the EU and Irish government organising extra imports of feed. However, according to a Teagasc scientist, using this safety valve may not be possible in the future given that European Green Deal policies are looking to stop our dependence on the global supply chain of feed, as it is contributing to the destruction of tropical rainforests and increased carbon emissions. Interviewees were also concerned that future drought could bring serious water shortages, particularly if intensification continues. Peak milk production and therefore water demand coincide with the summer. During this period, dairy cows require up to 70 litres of water a day, and additional water is required for the milk production process and cleaning of equipment and buildings. While a lot of farms have access to mains water, many of the larger, more intense operations find it more cost-effective to privately manage water supplies. As a result, in 2018, some farms with large dairy herds ran out of water and had to abstract it from nearby rivers. For other river and waterway users, concerns related to the combination of low flows, high temperatures and reductions in water quality encouraging weed growth and adversely affecting fisheries, the function of freshwater ecosystems and their cultural and recreational value to society. In general, drought is seen as something that exacerbates existing catchment pressures from agriculture, water management and historical drainage policies.

4.5 Co-producing Knowledge for Better Drought Management: Barriers and Opportunities

In this section, we draw on drought-specific and drought-related literature, and the insights and experiences of CROSSDRO project participants, to (1) identify common barriers to the production of actionable knowledge and (2) propose opportunities for improving the production of knowledge that can guide researchers and practitioners in better managing drought. We conclude by elaborating on some of the benefits and potential pitfalls of knowledge co-production, discussing the important role of social science in drought research and recommending some directions for future research. This section is based on a paper published by Grainger *et al*. (2021), which interested readers can access for further details.

4.5.1 Barrier: droughts have different meanings

Droughts are often considered from an agricultural, hydrological, economic or ecological perspective. However, there can be no universal definition that addresses how droughts impact social systems

(Lloyd-Hughes, 2014; Kohl and Knox, 2016). Drought and its impacts mean different things to different people, depending on their specific interests, needs and experiences, and the specific context. How we define drought can draw out preconditioned biases and a priori alienate or empower different stakeholders, influencing which impacts, sectors and types of knowledge have greater legitimacy in a policymaking or decision-making process.

4.5.2 Barrier: droughts can be perceptually challenging

Purely conceptual or scientific characterisations of drought have limited relevance for many stakeholders, particularly when the spatial and temporal resolution of the information provided is not relevant for their context (Ferguson *et al*., 2016). Drought planning is a particular challenge if recent societal and institutional experiences of drought do not reflect actual risk due to long-term climate variability (Murphy *et al*., 2017). Rivers or reservoirs in a region may appear to be at normal levels because of careful management, but low soil moisture may be affecting rain-fed agricultural production. In fact, hydrological droughts can persist even after heavy rainfall or flooding.

4.5.3 Barrier: droughts are context specific

How people perceive and respond to drought is strongly related to past experiences and memories (Taylor *et al*., 1988). Throughout history, drought-prone societies have developed culturally embedded rules of thumb or heuristics derived from experiential knowledge and mental models of their local environment (Courkamp *et al*., 2019). In northern European countries, droughts are usually associated with hot weather, which, in turn, evokes positive memories of being outdoors and enjoying the sunshine (Bruine de Bruin *et al*., 2016). As a result, droughts are not always seen as major hazards that require long-term planning.

4.5.4 Barrier: droughts are difficult to predict

It is difficult to develop confident meteorological forecasts of drought more than 2 weeks in advance. In most regions of the world, the skill of seasonal forecasting is still not sufficient to develop accurate seasonal drought forecasts (Bechtold *et al*., 2008; Dutra *et al*., 2013). While recent studies have suggested some improvements in this skill (e.g. Davini and D'Andrea, 2020; Smith *et al*., 2020), current drought forecasting systems are still subject to high levels of uncertainty.

4.5.5 Opportunity: focus on co-producing rather than translating knowledge

Collaborative knowledge production (commonly referred to as "co-production") can be defined as a learning process that deliberately brings together diverse perspectives to co-create actionable knowledge and new practices (Bremer and Meisch, 2017; Lemos *et al*., 2018). Knowledge co-production should be interactive, iterative, context driven and problem focused and should involve deep engagement with non-scientific knowledge systems (Norström *et al*., 2020). Co-produced knowledge is more likely to be perceived as credible, salient and legitimate (Cash *et al*., 2003). While systematic assessments are rare (Arnott *et al*., 2020), co-production has been shown to increase the likelihood of knowledge use in decision-making (Lemos *et al*., 2018). Successful co-production is predicated on including a plurality of perspectives (Turnhout *et al*., 2020).

4.5.6 Opportunity: iteratively analyse stakeholder needs and context

Given the complex and multi-sectoral nature of drought, it is vital that a thorough analysis of potential stakeholders and their decision-making contexts is conducted prior to and throughout collaborations. Top-down "loading dock" approaches that focus solely on information provision often fail to consider the complexity and dynamism of local cultural sensitivities around the legitimacy of different types of knowledge systems (Cash *et al*., 2006). Uncritical mapping and selection of potential stakeholders (e.g. targeting only water managers) can reinforce existing narrow perceptions and power structures.

4.5.7 Opportunity: explicitly recognise diverse understandings of drought

Given the plurality of perspectives on drought, no single perspective can presume superiority over another or claim to have a definitive understanding of drought and potential solutions. The inclusion of multiple forms of knowledge has the potential to enhance knowledge use and build trust between researchers and drought-sensitive sectors. Any characterisation of drought that strives for societal relevance must consider what makes drought socially relevant in that particular context (Ferguson *et al*., 2016). We would therefore encourage researchers to support decision-makers in drought-sensitive sectors to develop their own drought definition, tailored to their own context. This can be achieved through collaborative ground-truthing of drought indicators with stakeholder knowledge (Bachmair *et al*., 2016) and an understanding of their specific needs (Estrela and Vargas, 2012).

4.5.8 Opportunity: create enabling institutional environments

Effective knowledge production requires collaboration between different sectors and knowledge systems, operating on various spatial and temporal scales. Currently, the links between community- and national-scale drought management are weak (Pulwarty and Sivakumar, 2014). This fragmented management context is exacerbated by science and institutional systems that are grounded in top-down modes of knowledge production and mobilisation. Drought researchers and planners might benefit from working through organisations operating at the interface between science and policy (known as boundary organisations (Guston, 2001)), to help connect different sectoral drought plans and knowledge systems (e.g. water supply and agricultural sector) (Hannaford *et al*., 2018). The use of climate information and related services within drought risk management has been promoted by several key international initiatives, including the United Nations Global Framework for Climate Services and the Integrated Drought Management Programme (Finnessey *et al*., 2016). However, Turnhout *et al*. (2020) show that these types of science-led initiatives are often dominated by dynamics that reinforce rather than mitigate existing uneven politics.

4.5.9 Opportunity: openly discuss and characterise uncertainty

Drought management is beset by scientific and socio-economic uncertainties that require joint knowledge and problem solving by researchers, practitioners and other societal actors. Decision-makers should have awareness of the uncertainty associated with different forms of knowledge and knowledge production processes (Fischhoff and Davis, 2014). It is therefore important to manage expectations carefully, and characterise uncertainties in a manner that is transparent, relevant and understandable to all stakeholders.

4.6 Conclusions

Drought perceptions vary considerably among scientific disciplines, stakeholders and economic sectors, and are subject to change as a function of hazard severity, and socio-economic and environmental conditions. Context is crucial, with drought being associated with very different meanings and experiences in time and space. These scientific, perceptual and contextual challenges have made it difficult to engage with different sectors on anything other than a reactive basis (Wilhite, 2012). To overcome these barriers, we urge those involved in drought risk management to embrace co-production as a model of engagement and knowledge production. This will require researchers to become partners in knowledge creation rather than solely producers of knowledge, and to recognise multiple ways of understanding drought risk.

5 Conclusions

Droughts are complex hazards that are difficult to define, with impacts across multiple sectors. In Ireland, the 2018 drought exposed considerable vulnerability. The AXIS/JPI-funded CROSSDRO project sought to better understand long-term variability and change in droughts and their cross-sectoral impacts on the European and catchment scales, focusing on the Boyne catchment in eastern Ireland. From an Irish perspective, the project contributes the conclusions outlined below.

5.1 Meteorological Droughts

The CROSSDRO project compiled a long-term dataset (1850–present) of quality-assured precipitation records for the analysis of meteorological droughts across Europe. Long-term precipitation records from across Europe show that trends towards an increase in meteorological drought in the summer months are most notable for Ireland and the UK. These trends are most apparent in the eastern half of the island of Ireland. In other seasons and on an annual timescale, trends indicate a decreasing drought magnitude. However, it is important to highlight that a decreasing trend does not negate the possibility of extreme droughts occurring. For instance, the drought of spring 2020 recorded at Phoenix Park in Dublin was the most extreme drought (as measured using SPI-3) dating back to 1837, despite a trend for increasing precipitation in spring. It is not possible at present to attribute observed trends to anthropogenic climate change given the dominance of natural variability in precipitation records. While an increase in summer droughts is expected with climate change, consistency does not imply causality.

5.2 Hydrological Droughts

The CROSSDRO project collated a dense network of river flow gauges across Europe, covering the period 1962–2017, for the analysis of hydrological drought. For Ireland, trends indicate decreasing drought in the winter months and increasing drought in late spring and early autumn. However, these trends are statistically significant for only a few catchments. Negative trends in the duration of drought events predominate in Irish catchments in the period of analysis. The period of records available to assess hydrological droughts is short relative to the multi-centennial records available for assessing meteorological droughts. The analysis of hydrological droughts from flow reconstructions developed by O'Connor *et al*. (2022) for the period from 1900 onwards indicates a long-term trend towards increases in summer droughts, consistent with analysis of meteorological droughts. On the European scale, the largest increases in hydrological droughts were found in southern Europe, particularly in the Iberian Peninsula. These changes were not driven by precipitation change. Increases in AED with rising temperatures, together with land use changes and increases in water demand, are the most likely drivers.

5.3 Drought in the Boyne Catchment

The CROSSDRO project developed an extended catalogue of meteorological droughts for the Boyne catchment extending back to 1850. Despite the impacts of the 2018 drought, this drought event does not even rank in the top 10 most severe drought events from long-term records. The Boyne catchment has been extensively affected by arterial and land drainage. Our analysis found little impact of these disturbances on hydrological drought in the catchment. However, this is a first-pass analysis, and the impact of drainage should be further examined using daily flows rather than standardised drought indices, as were used here. Hydrometric data rescue in arterially drained catchments, carried out by De Smeth *et al*. (2023), will further facilitate the assessment of arterial drainage impacts on hydrological drought.

Data for tracking and quantifying drought impacts are lacking in Ireland. We show that newspaper archives can be used to assess the socio-economic impacts of historical droughts on the catchment scale. In addition, we show that drought impacts recorded in newspaper archives can be used to identify which drought metrics and accumulation periods best match impacts in specific sectors. This could inform the development of drought monitoring strategies. Development of the Irish Drought Impact Database (Jobbová *et al.*, 2022) will facilitate the extension of this approach to other catchments, while O'Connor *et al*. (2023) detail additional statistical approaches to linking drought metrics and impacts. Additional novel indicators of drought impacts, such as Google Trends data, may also prove useful in tracking the development of droughts and drought impacts on regional scales (Wilby *et al.*, submitted).

5.4 Towards a Better Understanding of the Impacts and Management of Droughts

Interviews with a wide range of stakeholders in the Boyne catchment and nationally highlighted diverse perspectives on drought, and the range of impacts experienced across sectors, including water management, agriculture, forestry, waterway navigation and fisheries, and in relation to ecosystems. For agriculture, droughts were reported as having significant impacts on grass growth, fodder management and costs, water demands in the dairy sector, and yields in arable farming and horticulture. Interviewees also highlighted how national strategies have created vulnerabilities through increases in the number of dairy cattle and the associated demands on and costs of water and fodder during droughts, and soil degradation in arable farming. The drought in 2018 presented serious challenges for livelihood security, with individual farmers highlighting a lack of support structures. For peatlands, stakeholders identified impacts related to excess drying and wildfire risks, and peatland ecology and degradation. Past drainage has served to increase peatland vulnerability to droughts, while an increase in drought frequency and/or magnitude would pose challenges for peatland restoration.

For water management, droughts were associated with supply issues, especially for private wells and group water schemes. Reduced water levels created problems for abstractions, reduced water quality and increased competition for resources. Drought impacts are made more problematic as a result of increasing water demands, typically driven by increases in local populations due to new developments and people moving away from the use of private wells; increased farm demands due to higher stocking rates; and an increase in per person demand due to increasingly affluent lifestyles. Counteracting this is a general improvement in the management of water supply (e.g. leakage rates, while still high, are much better now than in the past, and are continuing to improve because of funding being available) and the development of more resilient supply sources and networks.

For canals and waterways, droughts were associated mainly with problems of weed growth, navigation and increased competition for resources, while river droughts were associated primarily with restrictions on fishing and reduced fish health. For forestry, stakeholders highlighted the impact of drought on tree deaths and, in particular, problems for plantations on peatlands. Interviewees highlighted the need for irrigation and the importance of species diversity in increasing resilience to drought.

The co-production of knowledge on droughts facilitates better management. By moving beyond merely translating scientific knowledge and, instead, iteratively analysing stakeholder needs and explicitly recognising stakeholders' diverse understanding of droughts, more enabling institutional environments can be created. Key challenges include differences in the meaning of drought for different stakeholders, the perceptually challenging and context-specific nature of droughts, and the difficulties in predicting the occurrence, magnitude and duration of droughts.

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Abbreviations

AED	Atmospheric evaporative demand
DAFM	Department of Agriculture, Food and the Marine
DHLGH	Department of Housing, Local Government and Heritage
EPA	Environmental Protection Agency
IFA	Irish Farmers' Association
MK	Mann–Kendall
NFGWS	National Federation of Group Water Schemes
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SPI-3	Standardised Precipitation Index computed on a 3-month timescale
SPI-6	Standardised Precipitation Index computed on a 6-month timescale
SPI-12	Standardised Precipitation Index computed on a 12-month timescale
SRI	Standardised Runoff Index
SSI	Standardised Streamflow Index
WI	Waterways Ireland

Appendix 1 Publications Arising from the CROSSDRO Project

Conradt, T., Engelhardt, H., Menz, C., Vicente-Serrano, S.M., Alvarez Farizo, B., Peña-Angulo, D., *et al*. (2023). Cross-sectoral impacts of the 2018–2019 Central European drought and climate resilience in the German part of the Elbe River basin. *Regional Environmental Change* 23: 32.

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An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
> Sceitheadh fuíolluisce uirbigh;
> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
> Foinsí radaíochta ianúcháin;
> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
> Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
> Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
> Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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