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epa Research

HydroPredict: Ensemble River Flow Scenarios for Climate Change Adaptation

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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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- 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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- Publish Ireland's greenhouse gas emission inventories and projections;
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- Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
- Produce the State of Ireland's Environment and Indicator Reports;
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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

HydroPredict aims to advance understanding of how climate change will affect river flows and drought events over the coming decades. Using the latest climate models and emissions storylines, the research assessed the impacts of climate change on flow conditions and droughts across 37 river catchments. Higher greenhouse gas emissions are associated with large reductions in average summer and annual low flows. For winter, increases in average flows are projected. If ambitious greenhouse gas reductions are achieved, more moderate reductions in summer and low flows are projected by the middle and end of the century. Changes in meteorological droughts in Ireland are driven by a transition to wetter winters and drier summers, together with increased evapotranspiration losses during summer and late spring months, leading to more frequent spring and summer droughts. The magnitude of future drought changes depends on future greenhouse gas emissions, with the most substantial changes found for higher emissions. Results arising from this project highlight the importance of temperature increases and larger evapotranspiration losses to future changes in droughts. The eastern and midland regions are expected to experience the greatest increases in drought magnitude, frequency and duration.

Informing policy

HydroPredict results have relevance for climate change adaptation planning across multiple sectors, particularly agriculture, biodiversity and water resources management, as well as for local-scale impacts and adaptation assessments. The projected changes in low flows and droughts would pose challenges for water management, especially in the context of growing water demand. Groundwater resources, crucial for water provision, particularly in the midlands, may be influenced by changes in winter drought frequency and magnitude, possibly affecting recharge potential. The agricultural sector, particularly grass-fed dairy farming, relies heavily on consistent grass growth. The projected increase in spring and summer droughts could have adverse effects on grass growth and thus affect the sector. In addition, drought events can lead to degraded water quality, negatively affecting riverine species and habitats. The exact impact of future drought changes on water quality remains poorly understood and requires further research.

Developing solutions

Adapting to climate change in the water sector should place an increased emphasis on addressing the changing nature of droughts, especially across sensitive sectors. Existing vulnerability was evident during drought conditions in 2018, emphasising the need for adaptive measures. HydroPredict shows that success in reducing greenhouse gas emissions globally will be crucial to avoiding the most severe reductions in low flows and the increased severity of future droughts in Ireland. Nationally and locally, priority should be given to better monitoring of droughts and their impacts. Databases of historical drought impacts and improved monitoring systems based on standardised drought indices that include evaporative losses can assist in adaptation planning.

EPA RESEARCH PROGRAMME 2021–2030

HydroPredict: Ensemble River Flow Scenarios for Climate Change Adaptation

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EPA Research Report

Prepared for the Environmental Protection Agency

by

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DISCLAIMER

This report is based on research carried out/data from 2018 to 2022. 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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Executive Summary

HydroPredict aimed to assess the impacts of climate change on water resources in Ireland. The project examined future projections of low flows and droughts across 37 river catchments using an ensemble of climate models from the Coupled Model Intercomparison Project Phase 6 forced by three shared socioeconomic pathway (SSP) scenarios: SSP126, SSP370 and SSP585.

The results indicate wide ranges of plausible changes in seasonal mean and low flows. Higher emissions pathways (SSP370 and SSP585) show substantial reductions in summer mean flows and annual low flows (Q95), while winter mean flows are expected to increase. If ambitious greenhouse gas reductions are achieved (SSP126), more moderate reductions are projected by mid-century and the end of the century. In the case of spring and autumn flows, the direction of change remains unclear.

In addition, the project aimed to assess future changes in meteorological drought characteristics at a national scale. This was done by utilising the EURO-CORDEX ensemble of regionally downscaled climate model projections and applying standardised drought indicators. The focus was on quantifying changes in drought frequency, magnitude and duration across Ireland for the 2080s relative to the present, considering two emissions pathways representing moderate- and high-emissions futures: Representative Concentration Pathway (RCP) 4.5 and RCP8.5.

The study found that changes in meteorological droughts are driven by a transition to wetter winters and drier summers, together with increased potential evapotranspiration (PET) losses during summer and late spring months, leading to more frequent spring and summer droughts. The magnitude of future drought changes depends on the emissions pathway, with the most substantial changes observed under the RCP8.5 scenario. Different drought indicators yield varying results, with changes in the Standardised Precipitation Index (SPI) being more moderate than changes in the Standardised Precipitation Evapotranspiration Index (SPEI). This highlights the importance of PET in assessing future drought risks, and we recommend using SPEI, rather than SPI, for monitoring droughts.

Lastly, HydroPredict examined how changes in meteorological droughts propagate through catchments to impact river flows and groundwater. Changes in monthly and seasonal precipitation drive changes in drought magnitude and frequency in each catchment. Summer precipitation experiences large reductions, with an ensemble mean reduction of approximately 40% by the 2080s. These reductions in summer precipitation lead to increased drought severity and frequency by mid-century, as observed through various drought indices. Winter and spring precipitation influences catchment wetness and groundwater storage, setting antecedent conditions. Catchments with limited groundwater storage show a notable increase in the probability of drought propagation. The results indicate that hydrological drought shows larger ranges of change than meteorological drought, highlighting the non-linear translation of meteorological to hydrological drought and the associated uncertainty of hydrological modelling.

These changes in drought dynamics, along with the magnitude and frequency of drought events, could have significant implications for water resources and agriculture in Ireland, and eastern and midland regions are expected to experience the greatest increases in drought magnitude, frequency and duration. These changes would pose challenges for water management, especially in the context of growing water demand. Groundwater resources, crucial for water provision, particularly in the midlands, may be influenced by changes in winter drought frequency and magnitude, potentially impacting recharge potential. The agricultural sector, particularly grass-fed dairy farming, heavily relies on consistent grass growth. The projected increase in spring and summer drought frequency and magnitude could have adverse effects on grass growth and thus impact the sector. In addition, drought events can lead to degraded water quality, negatively affecting riverine species and habitats. The exact impact of future drought changes on water quality remains poorly understood and requires further research.

Adaptation planning should prioritise understanding and addressing the changing nature of droughts across sensitive sectors. Existing vulnerability was evident during drought conditions in 2018, emphasising the need for adaptation. Databases of historical drought impacts, and improved monitoring systems based on standardised drought indices, can assist in adaptation planning. Finally, it is important to consider that this analysis assumes no changes in land use, which is unlikely to be the case. Land use changes, driven by greenhouse gas mitigation strategies such as afforestation and rewilding, can influence drought risk. Future research should explore scenarios that incorporate both climate and land use change to better understand their combined impact on droughts.

1 HydroPredict Aims and Objectives

1.1 Introduction

Climate change and water-related hazards are closely linked. Climate change impacts of relevance to the water sector include more frequent, severe and persistent droughts, more frequent, widespread and extreme floods, and more episodic and harmful water pollution episodes (Wilby and Murphy, 2018). At the European scale, numerous studies have highlighted the risk of projected changes in low flows and drought because of climate change. For example, Roudier *et al*. (2016) examined potential future changes in extreme low flows (10- and 100-year return period) across Europe under a 2°C global warming scenario and found increases in drought duration and decreases in flow, highlighting Ireland as a hotspot for both floods and droughts, even at modest temperature increases.

Despite this risk, little work has been conducted to explore in detail the impacts of climate change on low flows and drought for Ireland's complex hydrology. Hence, coping with a more variable water supply, against a backdrop of rising demand, presents significant challenges. In meeting these challenges, information on and understanding of (i) past hydro-climatic variability and change and (ii) ongoing change in river flows through focused monitoring networks, and an assessment of climate change impacts into the future, are necessary to underpin the adaptive capacity of many sectors that rely on safe and sustainable water resources.

Recent work in Ireland has been successful in improving our understanding of variability and change, and monitoring of ongoing changes. Work on developing quality-assured long-term historical rainfall networks for Ireland (Noone *et al*., 2016) has revealed the extent to which Ireland has been subject to past drought, well beyond the experience of recent decades (Murphy *et al*., 2017; Noone *et al*., 2017). The value of such datasets is evidenced by the fact that water managers are now using these historical drought catalogues to reconsider vulnerability and assess existing drought plans. In terms of monitoring ongoing changes in surface water resources, Murphy *et al*. (2013) developed the Irish Hydrometric Reference Network. This is a network of catchments across the island (north and south) that minimise confounding factors (e.g. urbanisation, land use change), have good-quality rating curves and have sufficiently long records to allow the detection and quantification of the impacts of climate variability and change in river flows. The network is currently undergoing an update, and this will be critical to identifying emerging climate change signals in river flows over the coming years. For monitoring droughts, Úisce Éireann and Met Éireann track variation in the Standardised Precipitation Index to assess meteorological drought risk (Irish Water, 2021, Jobbová *et al*., 2023).

To date, assessment of climate change impacts on Irish hydrology has been dominated by investigations into future flood risk, perhaps due to the occurrence of major episodes of flooding in recent years (e.g. Broderick *et al*., 2019). The assessment of climate change impacts for mean and low flows, together with drought events, has lagged behind, despite the demand for improved knowledge for water management, drought planning, and water quality and ecosystem issues as part of the Water Framework Directive. There has been no national-scale assessment of climate change impacts on low flows and drought, despite the availability of large ensembles of global and regional climate models (RCMs). Such information is necessary to help guide effective adaptation in a sector that underpins societal and environmental wellbeing and economic vitality.

Assessments of climate change impacts on river flows and droughts typically follow a modelling chain that is associated with a cascade of uncertainty (Clarke *et al*., 2016). For example, when assessing future changes in river flows, climate models forced with different emissions pathways are downscaled (statistically or dynamically) and used to force one or more hydrological models to assess future changes against a reference period representing current conditions (Bastola *et al*., 2011). Previous research has shown the importance of climate model selection in influencing the range of change simulated at local scales, indicating the importance of using a large ensemble of climate models to more fully capture plausible ranges of change in key variables (Clarke *et al*., 2016; Smith *et al*., 2018). Others have shown that the choice of hydrological model and decisions taken calibrating them can significantly alter projected changes in low flows, with hydrological model uncertainty being important for the assessment of low flows and hydrological drought (Seiller *et al*., 2017; Vetter *et al*., 2017).

1.2 Research Aims and Policy Relevance

With these gaps in knowledge and challenges in mind, HydroPredict sought to produce a national-scale assessment of climate change impacts on low flows and droughts using available ensembles of climate model projections to quantify plausible ranges of change. The project produced simulations of hydrological response under climate change to inform climate change adaptation planning in Ireland. In doing so, the project aimed to incorporate key uncertainties in future projections of low flows and droughts. To assess climate change impacts on mean and low flows, the project employed 12 global climate models (GCMs) that are part of the ensemble of climate models that constitute the Coupled Model Intercomparison Project Phase 6 (CMIP6), to assess changes in hydrological response across 37 catchments. Key uncertainties in the impact assessment modelling chain stemming from GCMs, emissions pathways, bias correction approaches and the use of different hydrological models were evaluated. From the resultant simulations, the project sought to evaluate changes in key mean and low flow metrics of relevance to water managers to inform plausible ranges of change that can be expected for future time periods under different emissions pathways.

Given the lack of information on future changes in drought at a national scale, HydroPredict also aimed to assess future changes in the characteristics of meteorological droughts. For this purpose, the project employed the EURO-CORDEX ensemble of regionally downscaled climate model projections, which allows spatial evaluation because of the grid-based nature of this ensemble. Using standardised drought indicators, the project aimed to quantify changes in drought frequency, magnitude and duration across the country for the 2080s relative to present for two emissions pathways, namely Representative Concentration Pathway (RCP) 4.5 and RCP8.5.

Finally, the project aimed to assess how changes in meteorological droughts propagate through the catchment system to impact on river flows and groundwater. For this purpose, a smaller number of catchments were evaluated in depth to understand how initial meteorological deficits give rise to soil moisture, river flow and groundwater deficits, and how the likelihood of propagation from one component of the hydrological system to another is likely to change in future.

HydroPredict results are relevant from several policy perspectives. Ireland’s national climate objective is to achieve the transition to a low-carbon, climate-resilient and environmentally sustainable economy by 2050. Critical to a climate-resilient and sustainable economy is understanding risks to water and a well-adapted water resource management sector. The National Adaptation Framework (2018) requires the mainstreaming of climate adaptation into all national- and local-level policymaking and decision-making. To achieve this requires information on expected changes in water resources and extreme events. HydroPredict is directly aimed at facilitating better data for decision-making at local, regional and national scales. Project Ireland 2040, Ireland’s National Development Plan, highlights the strategic importance of (i) sustainable management of water, waste and other environmental resources, (ii) transition to a low-carbon, climate-resilient society and (iii) a strong economy supported by enterprise, innovation and skills. Each of these strategic outcomes requires safe and sustainable water resources, which can be achieved only through evidence-based planning, which HydroPredict seeks to support. Research outputs will also be of value to the successful implementation of the Water Framework Directive, underpinning the development and assessment of river basin management plans and decision-making for climate change.

1.3 Report Structure

The remainder of this report is structured as follows. Chapter 2 provides an overview of climate change impacts on mean and low flows for Irish catchments using the CMIP6 ensemble. Chapter 3 considers changes in the characteristics of droughts with climate change using the EURO-CORDEX ensemble. Chapter 4 then considers how changes in drought are likely to propagate through the catchment system for a subset of catchments. Finally, in Chapter 5, key conclusions and recommendations for policy are provided. Given the available space, the chapters provide only an overview of key findings. Each chapter is supplemented by and draws from research papers published over the course of the project. Interested readers are encouraged to consult these more detailed publications (Meresa *et al*., 2022, 2023; Meresa and Murphy, 2023), all of which are open access.

2 Future Changes in Mean and Low Flows for Irish Catchments

2.1 Introduction

Climate change is expected to impact on catchment hydrology through changes in precipitation and evapotranspiration. Key to successful adaptation is understanding the range of plausible changes that may materialise, with impacts potentially affecting water resource management, water quality, aquatic ecosystems, hydro-power generation and economic activity. Despite the vulnerability revealed by recent drought events in summer 2018 (Falzoi *et al.*, 2019), together with significant pressure on water supply systems and water quality (Kelly-Quinn *et al.*, 2014), relatively little research has evaluated future changes in mean and low river flows for Irish catchments. Therefore, HydroPredict aimed to provide an assessment of the impacts of climate change on seasonal mean and annual low flows for Irish catchments. In doing so, we attempt to represent the plausible ranges of future change by employing 12 GCMs that constitute the CMIP6 (O'Neill *et al.*, 2016) ensemble, with each model forced using three shared socioeconomic pathways (SSPs) and two structurally different hydrological models. This chapter provides an overview of the implementation of steps in the modelling chain, together with key results. Full details of the analysis and results can be found in Meresa *et al.* (2022).

2.2 Data and Methods

2.2.1 Observed catchment data

Changes in future seasonal mean and annual low flows (flow exceeded 95% of the time) were assessed for 37 catchments, selected as having good-quality observed flows and to be broadly representative of Irish hydrological conditions. The distribution of selected catchments is shown in Figure 2.1, with catchment area ranging from 11 to 2418 km^2 (average 738 km^2). For each catchment, the observed data necessary for training and testing hydrological models were compiled and area averaged for the period 1976–2015. Gridded (1 km × 1 km) daily precipitation and temperature data were obtained from Met Éireann (Walsh, 2012) and used to extract catchment average series. Daily potential evapotranspiration (PET) was then derived from air temperature data using the method of Oudin *et al.* (2005). Daily discharge data for each catchment were obtained from the Office of Public Works (accessed via waterlevel.ie) and the Environmental Protection Agency (accessed via hydronet.ie).

2.2.2 Climate model projections and bias adjustment

For each catchment, daily precipitation and temperature data for the period 1976–2100 were extracted from 12 members of the CMIP6 ensemble of climate models. The models employed are listed in Table 2.1. CMIP6 models that show a high climate sensitivity (Zelinka *et al.*, 2020) are marked with an asterisk. We focus attention on projections from three SSPs representing a scenario of sustainability (SSP126), a rocky road marked by regional rivalry (SSP370) and a fossil fuel-dependent future (SSP585). These SSPs are consistent with radiative forcings (watts per metre squared) analogous to RCP2.6, RCP7.0 and RCP8.5, respectively. For each catchment, daily precipitation and temperature data were extracted for the closest land-based climate model grid overlying the catchment centroid. Series were then bias adjusted using the double gamma quantile mapping method for precipitation and empirical quantile mapping for air temperature (see Meresa and Murphy (2022) for details). Future estimates of PET were derived from bias-adjusted temperature data using the method of Oudin *et al.* (2005).

2.2.3 Hydrological models

The GR4J (Génie Rural à 4 paramètres Journalier; Perrin *et al.*, 2003; Coron *et al.*, 2017) and SMART (Soil Moisture Accounting and Routing for Transport; Mockler *et al.*, 2016; Hallouin *et al.*, 2020) hydrological

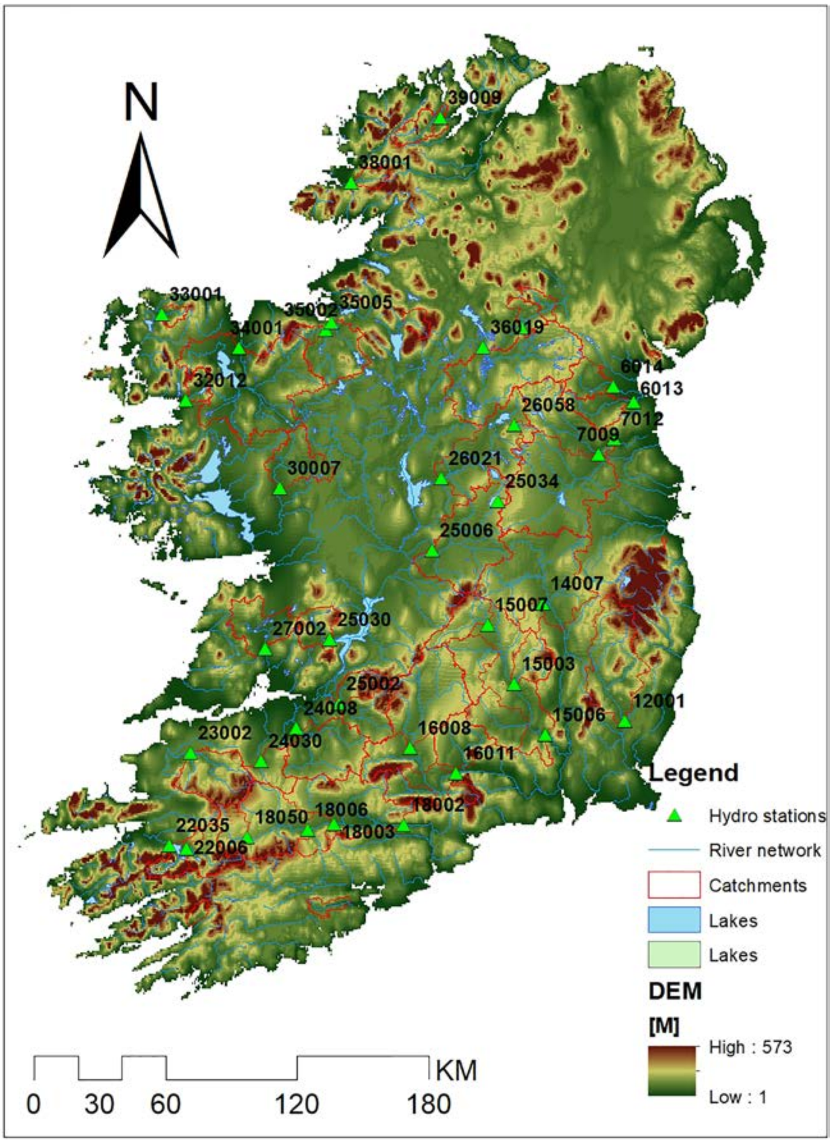


Figure 2.1. Distribution of catchments selected for analysis. Catchment boundaries are shown in red, while the green triangles represent the location of the gauging station in each catchment. The numbers represent the hydrometric codes used to identify each gauging station. Reproduced from Meresa *et al*. (2022); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

models were employed to simulate future changes in each catchment. Both models have been widely employed in previous studies of catchment hydrology in Ireland (e.g. Broderick *et al*., 2016; Golian *et al*., 2021; Murphy *et al*., 2023) and allow uncertainties from hydrological model structure in future simulations to be accounted for. Meresa *et al*. (2022) provide full details on the structure of each model. Before these models were used to simulate future changes, they were calibrated and evaluated for each catchment using observed data. Using Latin hypercube sampling (Murphy *et al*., 2006), 30,000 parameter sets were sampled from a uniform distribution representing each model parameter and then evaluated against observed flows in each catchment for the period 1990–2015, with the best 150 parameter sets retained for use in future simulations. Model performance was assessed using the Nash–Sutcliffe efficiency criterion derived from the log of flows (logNSE), the percentage bias and performance of the median simulation from both models in capturing various hydrological signatures representing the range of flow conditions in each catchment (see Figure 2.2). The median simulation of the retained parameter sets was used to evaluate changes in seasonal mean and low flows.

Table 2.1. Details of the 12 CMIP6 climate models included in the analysis

Code	Institute	Parent source ID	Institution ID
CM1*	Commonwealth Scientific and Industrial Research Organisation, Australia	ACCESS-CM2	CSIRO
CM2*	Met Office Hadley Centre, UK	UKESM1–0-LL	MOHC
CM3	Beijing Climate Center, China	BCC-CSM2-MR	BCC
CM4	NOAA Geophysical Fluid Dynamics Laboratory, USA	GFDL	NOAA-GFDL
CM5	EC-EARTH consortium, Europe	EC-Earth	EC-EARTH consortium
CM6*	National Center for Atmospheric Research, USA	CESM2	NCAR
CM7*	Met Office Hadley Centre, UK	HadGEM3-GC31-LL	MOHC
CM8	JAMSTEC, AORI, NIES and R-CCS, Japan	MIROC6	MIROC
CM9	Max Planck Institute for Meteorology, Germany	MPI-ESM1–2-HR	MPI-M
CM10	Meteorological Research Institute, Japan	MRI-ESM2–0	MRI
CM11	Norwegian Earth System Model (NorESM) Climate Modeling Consortium, Norway	NorESM2-LM	NCC
CM12*	Nanjing University of Information Science and Technology, China	NESM3	NUIST

Models marked with an asterisk are those showing high climate sensitivity.

AORI, Atmosphere and Ocean Research Institute; JAMSTEC, Japan Agency for Marine-Earth Science and Technology; NOAA, National Oceanic and Atmospheric Administration; NIES, National Institute for Environmental Studies; R-CCS, RIKEN Center for Computational Science.

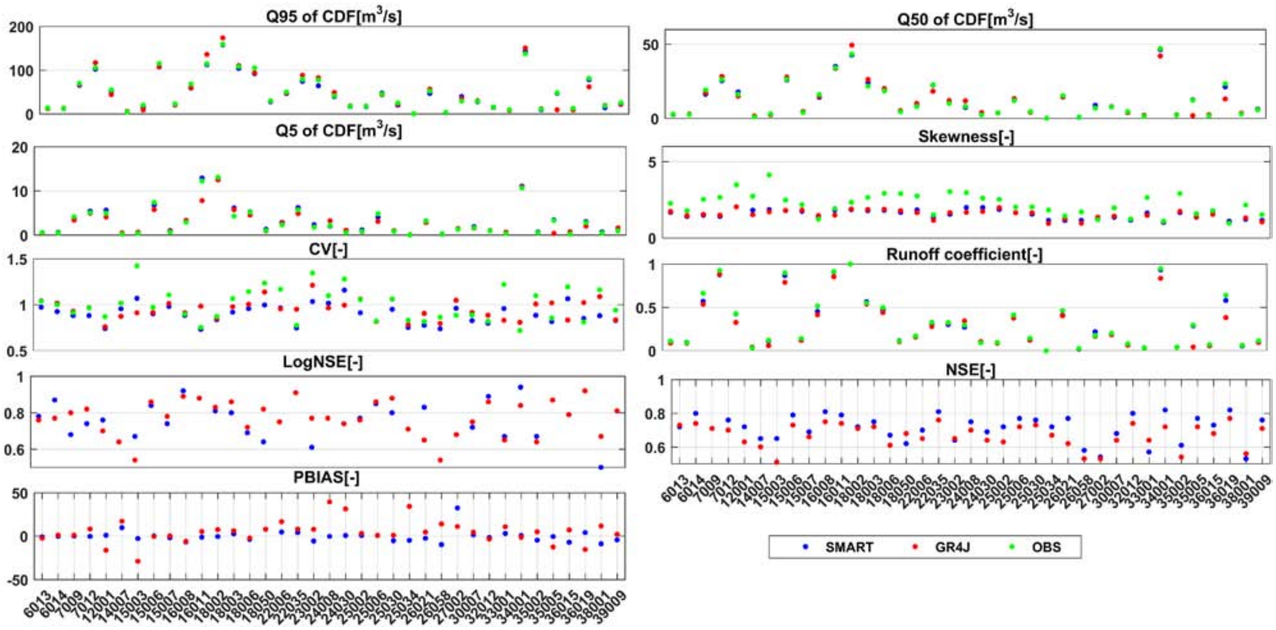


Figure 2.2. Performance of the GR4J and SMART hydrological models in simulating hydrological signatures in each catchment (including flow percentiles representing low, median and high flows (Q95, Q50, Q5), the skewness, coefficient of variation (CV) and runoff coefficient of observed flows), together with percentage bias (PBIAS), Nash–Sutcliffe efficiency (NSE) and logNSE skill scores for each catchment over the evaluation period (1990–2015). Reproduced from Meresa *et al.* (2022); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

2.3 Changes in Seasonal Flows

Bias-adjusted projections of precipitation and PET for each of the 12 CMIP6 climate models were used to force both hydrological models for the period 1976–2100 under three different SSPs (SSP126, SSP370 and SSP585). For each catchment, percentage changes in flows were evaluated for three future time periods (2020s: 2010–2039;

2050s: 2040–2069; 2080s: 2070–2099) relative to the baseline period, 1976–2005. Below, we summarise changes in seasonal flows across the catchment sample for each SSP. Meresa *et al*. (2022) provide a fuller analysis of changes and provide median percentage changes for each catchment/season/SSP/hydrological model, together with 90% confidence intervals (CIs), as look-up tables in their supplementary information section, allowing interested readers to examine results for any catchment in more detail.

2.3.1 SSP126 sustainable future

Figure 2.3 shows the percentage change in seasonal flows under SSP126 for each catchment, as simulated by the GR4J and SMART hydrological models. The following key results are discernible:

- For all seasons, projected changes span increases and decreases with no clear direction of change evident. The ranges of change in seasonal mean flows are larger for the SMART model. For both hydrological models, projected increases/decreases in each season become progressively larger when moving from the 2020s to the 2050s to the 2080s.
- The largest increases in winter flows were simulated by the SMART model for the 2080s, with a median increase of 12.6% across all catchments (CI 53.3% to 0.2%). Increases in winter flows for the 2080s for the GR4J model showed a median increase of 4.9% across all catchments (CI 21.1% to −4.7%).
- For spring mean flows, the GR4J model tends towards decreases, while the SMART model suggests increases. For example, for the 2080s, the GR4J model simulated a median reduction of −10.3% across all catchments (CI 1.4% to −19.9%), while the SMART model simulated a median increase of 4.4% (CI 38.3% to −10.9%).
- For summer mean flows, projected changes span increases and decreases for all future time periods. For the 2080s, the median change in summer flows across all catchments was 1.8% (CI 30.5% to −17.1%) for the GR4J model and −12.5% (CI 38.2% to −34.8%) for the SMART model.
- For autumn mean flows, the GR4J model tends towards increases, with the SMART model tending towards decreases. The median change simulated across catchments by the GR4J model for the 2080s is 18.2% (CI 42.1% to −1.1%), while for the SMART model a median change of −1.7% (CI 34.7% to −25.5%) is simulated.

2.3.2 SSP370 rocky road

Figure 2.4 shows the percentage change in seasonal flows under SSP370 for each catchment, as simulated by the GR4J and SMART hydrological models. The following key results are discernible:

- Winter flows tend to show increases under SSP370. The largest increases were projected by the SMART model, with a median increase of 13.4% across catchments by the 2080s (CI 32.2% to 2.9%). For the same time period, the GR4J model simulated a median increase of 6.9% (CI 23.1% to −1.8%). Increases in winter mean flows become progressively larger when moving from the 2020s through to the 2080s.
- For spring mean flows, the direction of change is unclear. For the 2080s, the GR4J model returned a median decrease of −6.0% (CI 5.6% to −23.6%), while the SMART model returned a median increase of 2.3% (CI 19.6% to −9.0%).
- For summer, projected changes from both hydrological models span a wide range of change from increases to decreases. The GR4J model shows the most substantial decreases, with a median reduction of −21.3% across catchments (CI 4.8% to −36.9%) by the 2080s. The
- equivalent simulation for the SMART model was −17.9% (CI 11.4% to −38.6%). For both hydrological models, decreases in summer flows become progressively more substantial when moving from the 2020s to the 2080s.
- For autumn mean flows, modest increases in flows are projected for the 2050s and 2080s, but large ranges are returned. For the 2080s, the GR4J model returned a median increase of 8.4% across catchments (CI 32.5% to −8.5%), while the SMART model returned a median increase of 2.3% (CI 29.9% to −12.6%).

2.3.3 SSP585 fossil fuel intensive

Figure 2.5 shows the percentage change in seasonal flows under SSP585 for each catchment, as simulated

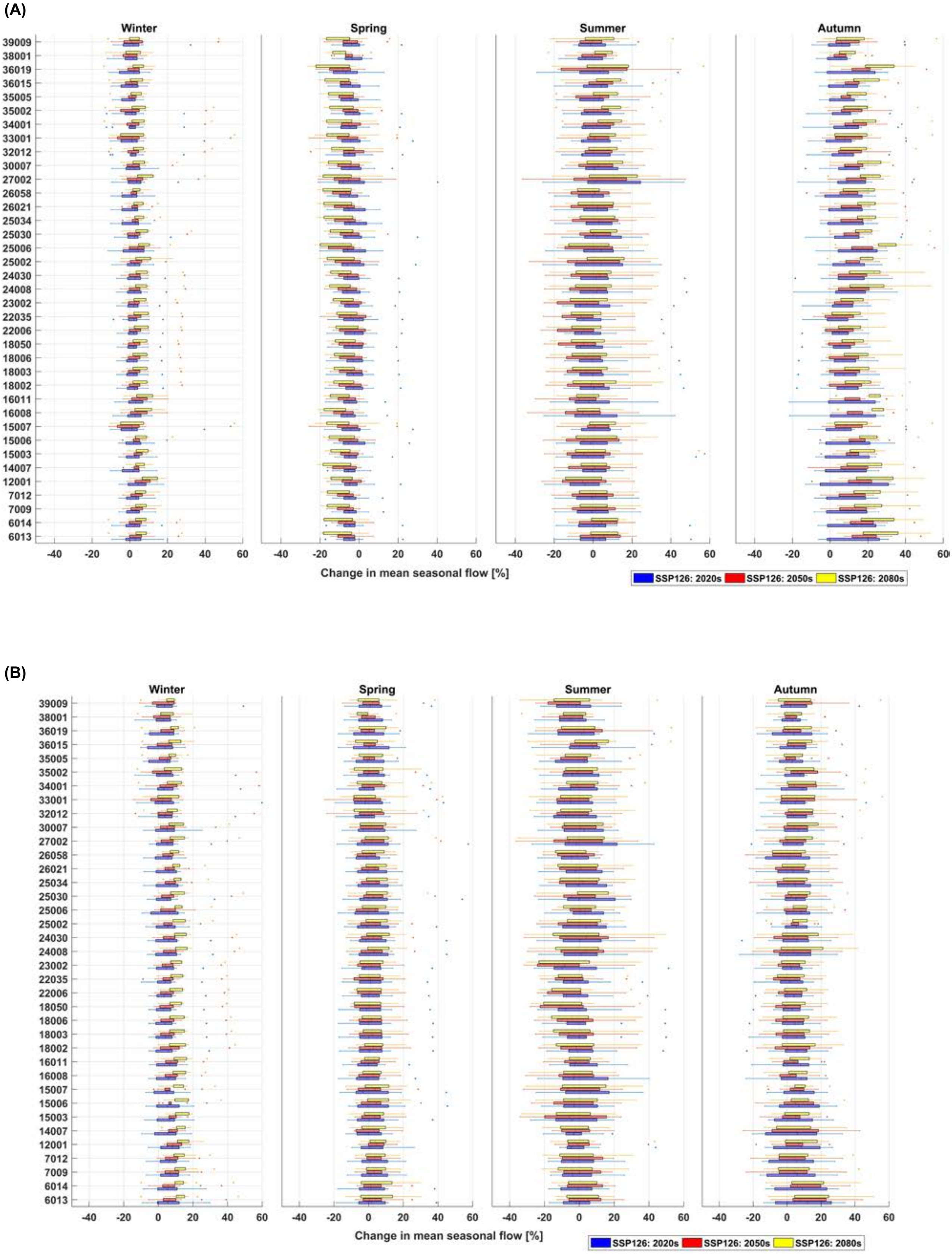


Figure 2.3. Projected percentage changes in seasonal flows derived from the GR4J model (A) and the SMART model (B) forced by the bias-adjusted outputs from 12 CMIP6 models under SSP126 for the 2020s (blue), 2050s (red) and 2080s (yellow) relative to the reference period, 1976–2005. Each catchment is represented by the gauge number given in Figure 2.1. Reproduced from Meresa *et al*. (2022); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

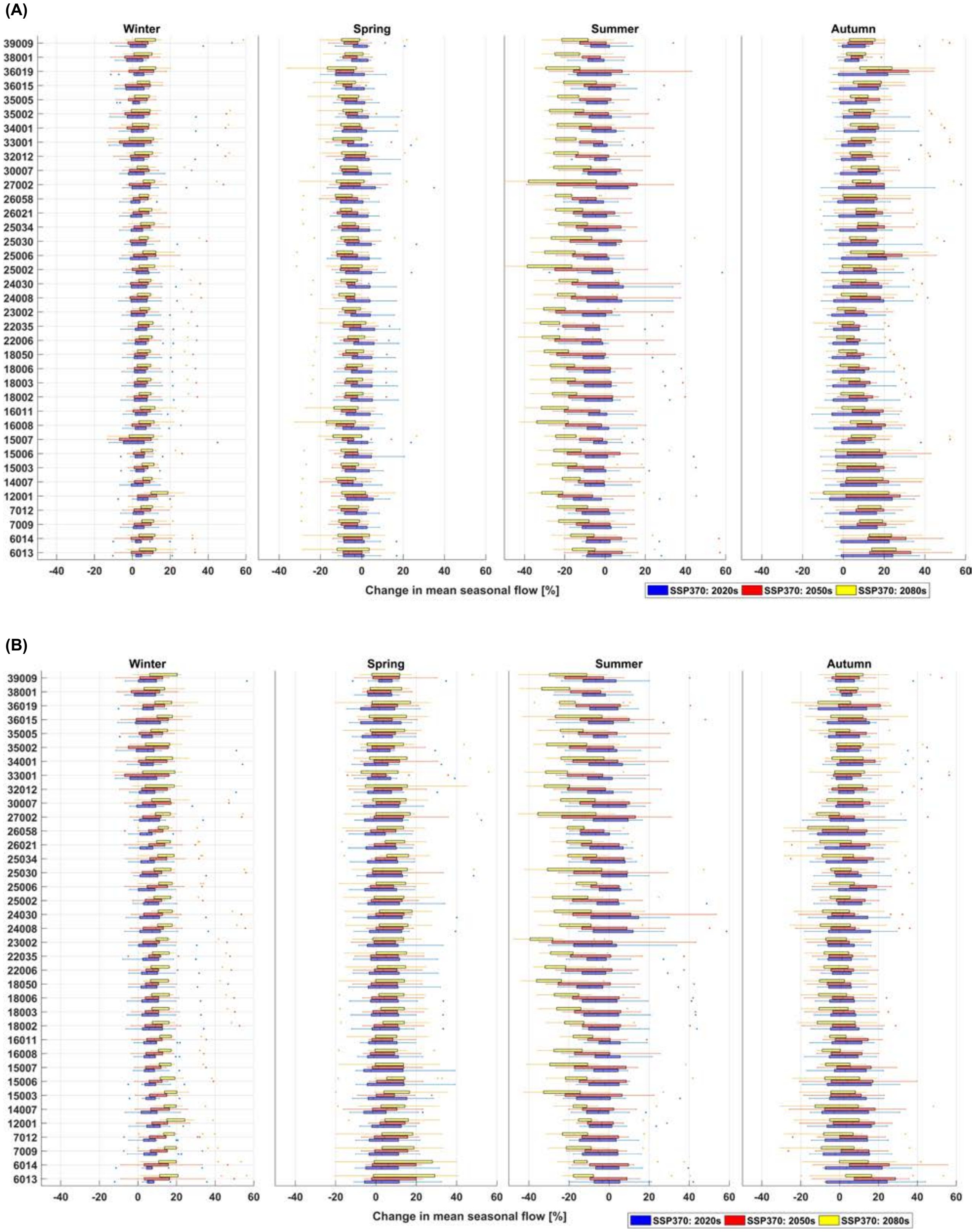


Figure 2.4. Projected percentage changes in seasonal flows derived from the GR4J model (A) and the SMART model (B) forced by the bias-adjusted outputs from 12 CMIP6 models under SSP370 for the 2020s (blue), 2050s (red) and 2080s (yellow) relative to the reference period, 1976–2005. Each catchment is represented by the gauge number given in Figure 2.1. Reproduced from Meresa *et al*. (2022); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

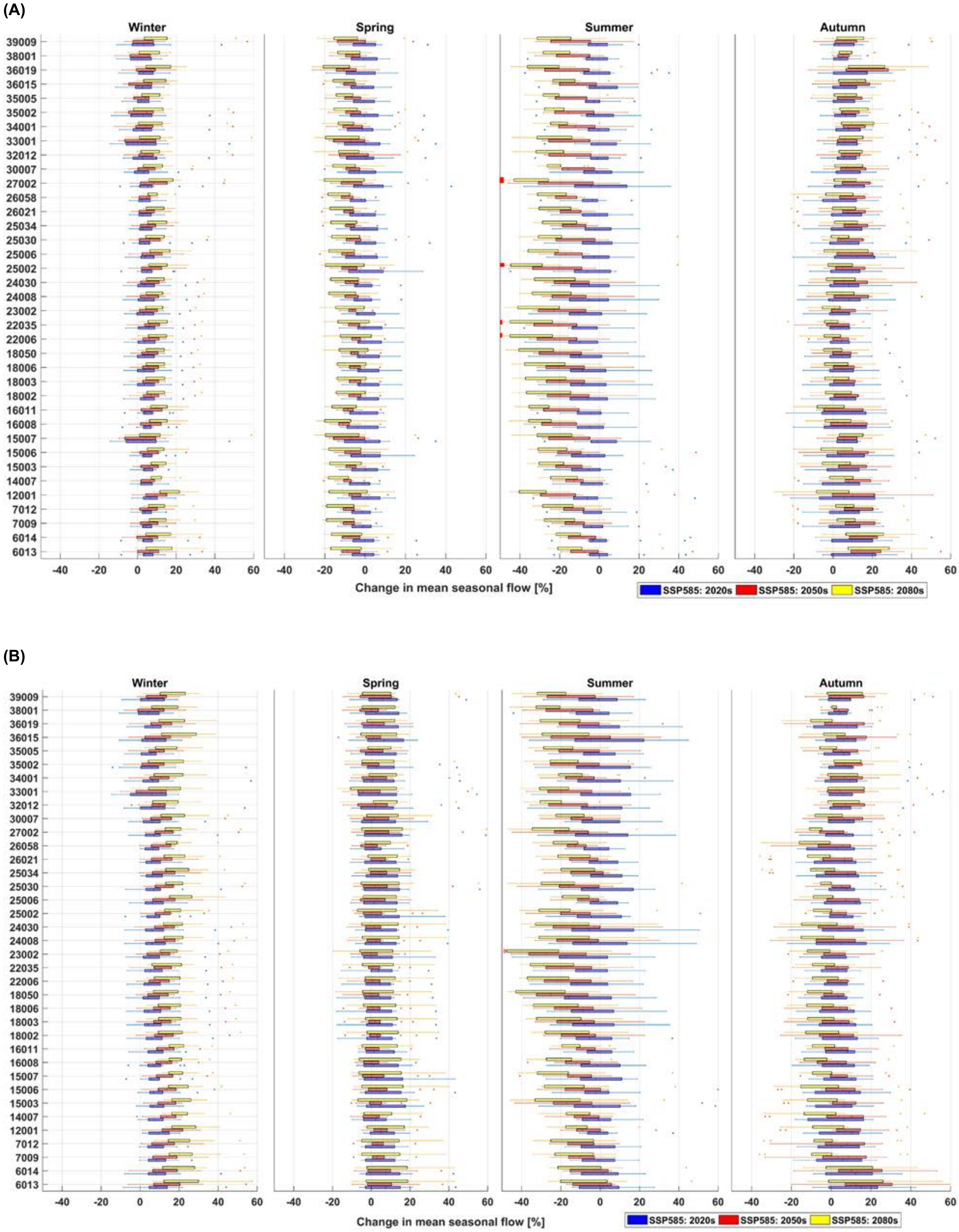


Figure 2.5. Projected percentage changes in seasonal flows derived from the GR4J model (A) and the SMART model (B) forced by the bias-adjusted outputs from 12 CMIP6 models under SSP585 for the 2020s (blue), 2050s (red) and 2080s (yellow) relative to the reference period, 1976–2005. Each catchment is represented by the gauge number given in Figure 2.1. Reproduced from Meresa *et al*. (2022); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

by the GR4J and SMART hydrological models. The following key results are discernible:

- Increases in winter mean flows become progressively larger as the century progresses. By the 2080s, the largest increases are simulated by the SMART model, with a median increase across catchments of 13.4% (CI 28.6% to 5.5%). The GR4J model shows a median increase of 8.5% (CI 29.6% to 0.1%).
- Even under SSP585, the direction of change in spring flows remains unclear, with both hydrological models spanning increases and decreases. Median changes from the GR4J model suggest progressively decreasing flows as the century progresses (2080s median −10.8%; CI 8.6% to −20.9%), while the SMART model showed increases (2080s median 4.9%; CI 19.2% to −15.4%).
- For summer, progressively larger decreases in flow are simulated when moving from the 2020s to the 2080s. Reductions are typically greatest for the GR4J model, with a median reduction in summer flows of −25.0% across catchments by the 2080s (CI −3.2% to −43.3%). Reductions simulated by the SMART model are more modest, with a median reduction of −10.8% simulated across catchments for the 2080s (CI 12.0% to −35.1%).
- For autumn, the direction of change is unclear, but median simulations from both models tend towards increases. For the 2080s, the SMART model returns a median increase of 1.8% across catchments (CI 28.9% to −12.7%). The GR4J model returns a median increase of 5.2% (CI 30.2% to −11.0%).

2.4 Changes in Annual Low Flows

Changes in annual low flows were evaluated using Q95; the flow exceeded 95% of the time during the reference period. Figure 2.6 presents the changes in Q95 for each future time period under SSP126, SSP370 and SSP585 for the GR4J and SMART models. For SSP126, the direction of change in low flows is uncertain. For the GR4J model, median reductions in Q95 across catchments of −3.4%, −6.0% and −1.7% are simulated for the 2020s, 2050s and 2080s, respectively. The range of changes are large, with CIs spanning 17.0% to −16.8% for the 2020s, 18.7% to −23.3% for the 2050s and 19.2% to −18.5% for the 2080s. Similar results were obtained with the SMART model. For SSP370 and SSP585, simulated changes tend more towards reductions in Q95, especially for the middle and end of the century. For SSP370, by the 2080s, the GR4J model returned a median reduction of −20.9% in Q95 across catchments (CI −2.5% to −38.2%), while the SMART model suggested a median reduction of −21.2% (CI −6.0% to −36.9%). SSP585 shows the most severe reductions. By the 2080s, the GR4J model returns a median reduction of −23.2% (CI −5.4% to −45.0%), while the SMART model returns a median reduction of −25.5% (CI −6.1% to −41.8%).

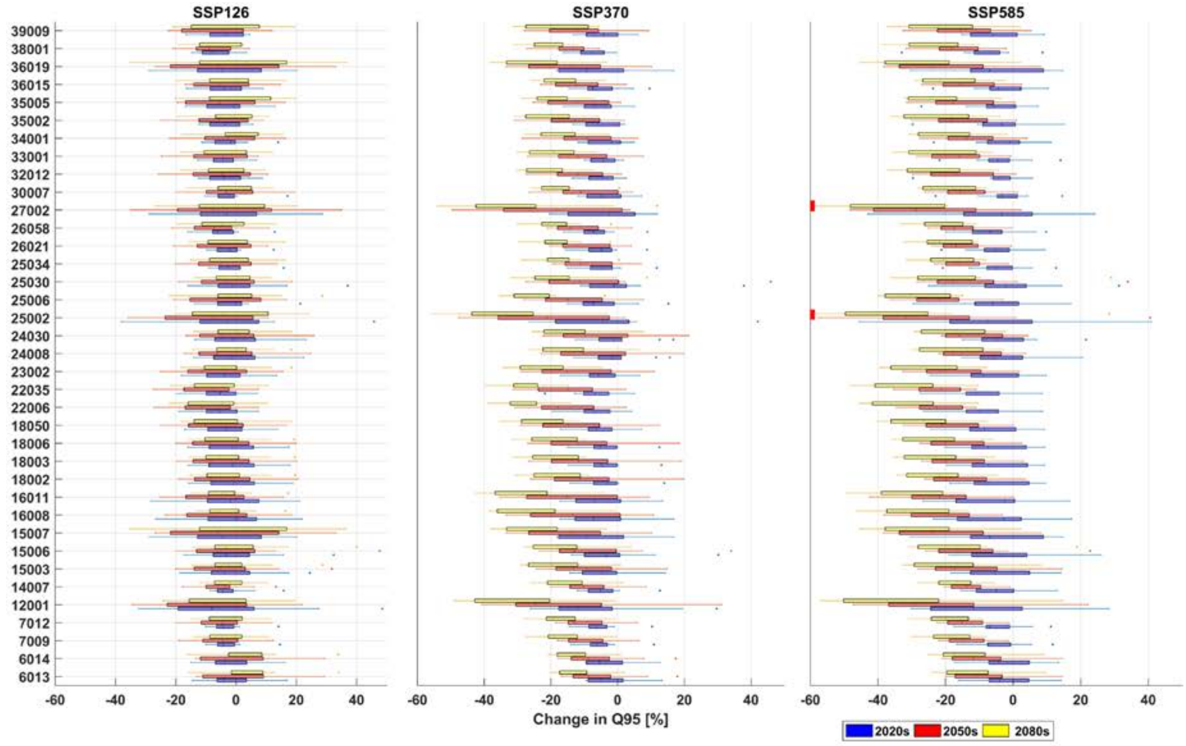
2.5 Avoided Impacts from Mitigation

To examine how efforts to reduce greenhouse gas emissions impact seasonal and low flows, we assessed differences in median changes between SSPs for the end of the century (2080s). Changes in annual low flows (Q95) are most sensitive to reductions in emissions (Figure 2.7). For both the SMART and GR4J models, SSP126 resulted in more modest changes in low flows than SSP370 and SSP585, indicating the importance of mitigation efforts in avoiding the most extreme impacts. For seasonal mean flows, the differences between SSPs are less obvious and at times depend on which hydrological model was employed (e.g. summer mean flows in Figure 2.7).

2.6 Conclusion

This research evaluated climate change impacts on seasonal mean and annual low flows for 37 Irish catchments. Changes were derived from an ensemble of 12 climate models from the CMIP6 archive, forced using three SSP scenarios (SSP126, SSP370 and SSP585). While only a synopsis of results is provided here, full details on methods and findings can be found in Meresa *et al*. (2022). Key advances include the consideration of multiple catchments, climate models, SSPs and hydrological models. However, we did not assess hydrological model parameter uncertainty (Wilby, 2005), or different downscaling or bias adjustment techniques (Meresa *et al*., 2021), while we assumed that the parameter sets derived to run our hydrological models during current conditions

(A)



(B)

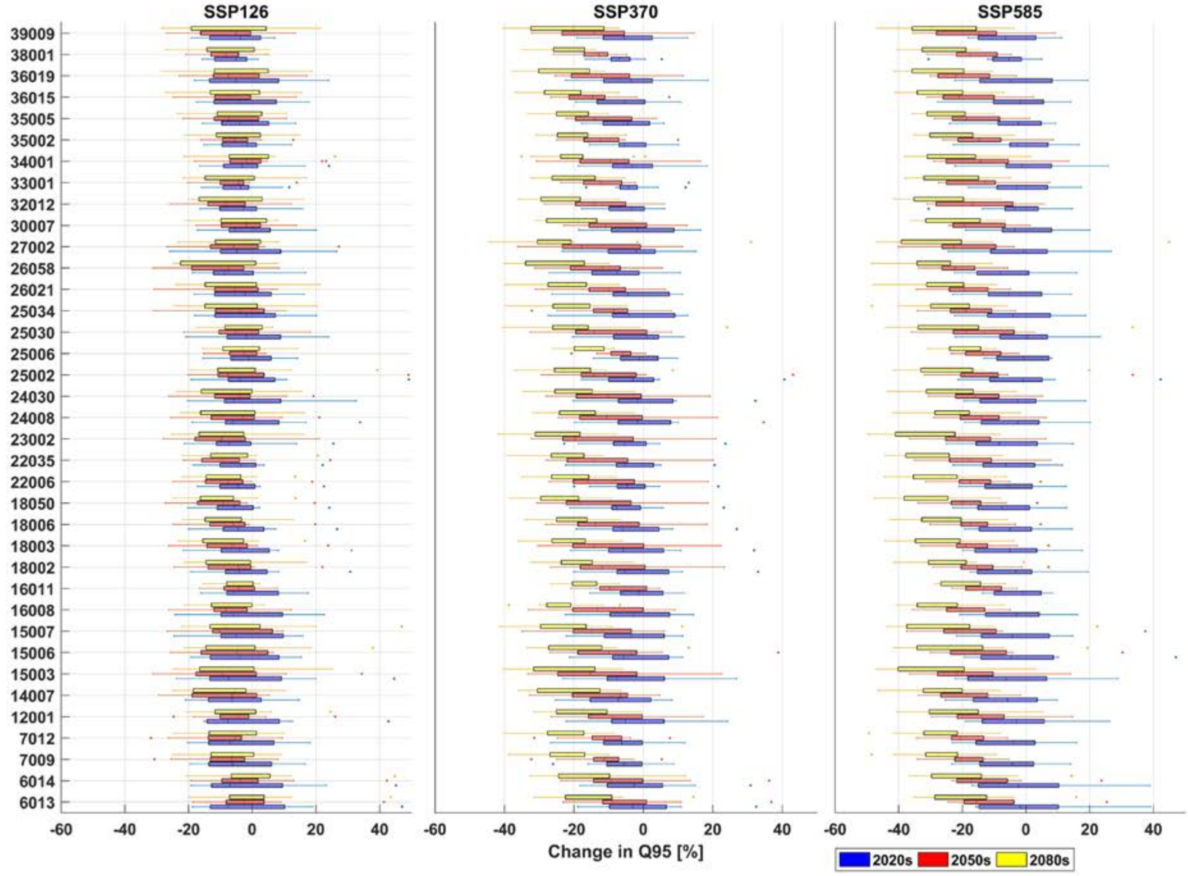


Figure 2.6. Simulated percentage changes in the annual Q95 for the 2020s, 2050s and 2080s relative to the reference period, 1976–2005, for each catchment, as simulated for SSP126, SSP370 and SSP585 for the GR4J model (A) and the SMART model (B). Each catchment is represented by the gauge number given in Figure 2.1. Reproduced from Meresa *et al*. (2022); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

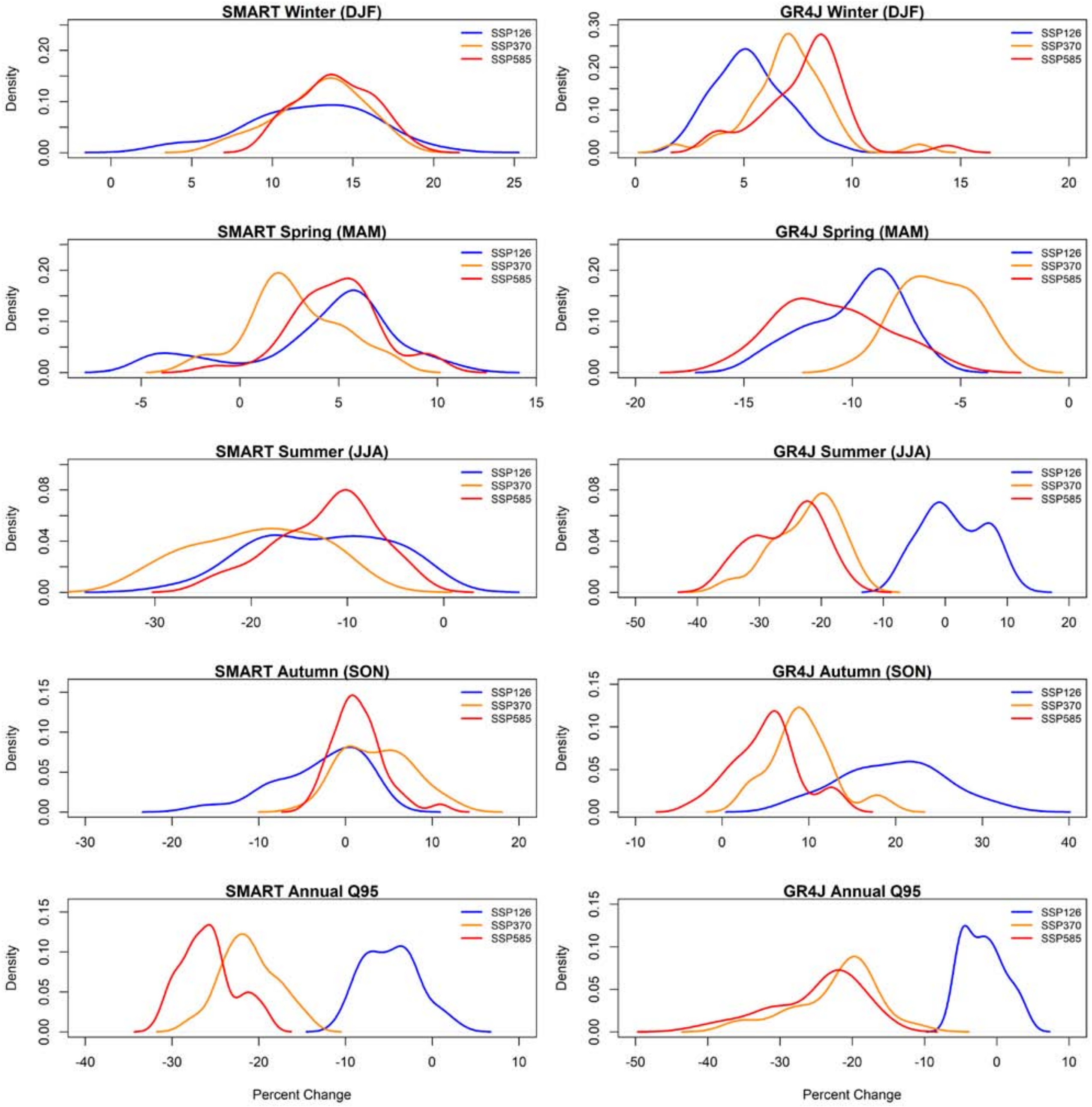


Figure 2.7. Median changes in the seasonal mean and annual low flows simulated by the SMART model (left) and the GR4J model (right) across all catchments for each SSP during the 2080s. Reproduced from Meresa *et al*. (2022); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

are transferable to future climates (Broderick *et al*., 2016). Future work should attempt to expand the consideration of uncertainties considered to further inform the plausible ranges of change that might be expected. Alternative approaches to the estimation of PET should also be considered, along with the robustness of findings for the small catchments in our dataset. Future work might also examine opportunities for constraining the internal hydrological pathways of the SMART model by constraining parameter selection using estimates of groundwater recharge, along with discharge observations to calibrate the model.

The results show wide ranges of plausible changes in the seasonal mean and low flows, with increases in the winter mean flows and large reductions in summer mean flows and annual low flows (Q95) for both hydrological models for higher emissions pathways (SSP370 and SSP585). Notably, more modest reductions in summer mean and low flows are evident by the middle and end of century if ambitious greenhouse gas reductions can be achieved (SSP126). For spring and autumn, large ranges of change are evident, but the direction of change is unclear. We found little evidence that CMIP6 climate models with high climate sensitivity produce simulated changes in precipitation outside the range of other ensemble members at the catchment scale.

3 Future Changes in Drought for the Island of Ireland

3.1 Introduction

Droughts are typically defined as periods of abnormally dry weather that persist for sufficient periods of time to create hydrological imbalance (Cook *et al*., 2004). The scientific community has defined drought in terms of how such imbalance results in different impacts, with droughts categorised as meteorological, agricultural, hydrological or socioeconomic drought. Droughts typically commence as a meteorological deficit and propagate to other domains over time. In Ireland, drought conditions in 2018 resulted in considerable impacts for agriculture and water resources, revealing specific vulnerabilities in these sectors (Dillon *et al*., 2019; Falzoi *et al*., 2019). Recent research has developed insight into historical droughts in Ireland, highlighting significant drought-rich periods in 1890–1910, 1921–1922, 1933–1934, in the 1940s and in the early and mid-1970s (Noone *et al*., 2017; Murphy *et al*., 2020; O’Connor *et al*., 2023). Analysing long-term quality-assured precipitation series across Europe over the period 1850 to present, Vicente-Serrano *et al*. (2022) found trends towards increased drought magnitude during summer for Ireland, although it is unclear whether such changes are due to anthropogenic climate change or natural climate variability, or a combination of both.

While the previous chapter assessed changes in precipitation and low flows with climate change (e.g. Meresa *et al*., 2022), little research has assessed how climate change is likely to affect future droughts on the island. Therefore, HydroPredict sought to address this knowledge gap by using bias-adjusted simulations from the EURO-CORDEX ensemble of climate change projections to assess changes in the magnitude, frequency and duration of droughts for the 2080s, relative to current conditions. We employ EURO-CORDEX because of the ensemble size (11 models) and the gridded nature of outputs, which allows consideration of spatial changes across the island. This chapter provides an overview of results, with full details published by Meresa and Murphy (2023).

3.2 Data and Methods

3.2.1 *Climate change projections*

We assess changes in drought at the grid scale and for five regions of Ireland classified as northern, western, eastern, south-eastern and southern (Figure 3.1). The climate change projections employed were derived from the EURO-CORDEX ensemble (Jacob *et al*., 2014; Giorgi and Gutowski, 2015) for 11 GCM/RCM combinations run at 0.11° resolution (≈12.5 km; see Table 3.1) under two RCPs (RCP45 and RCP85). We assess changes for the 2080s (2070–2099), relative to the reference period, 1976–2005. Daily air temperature and precipitation data

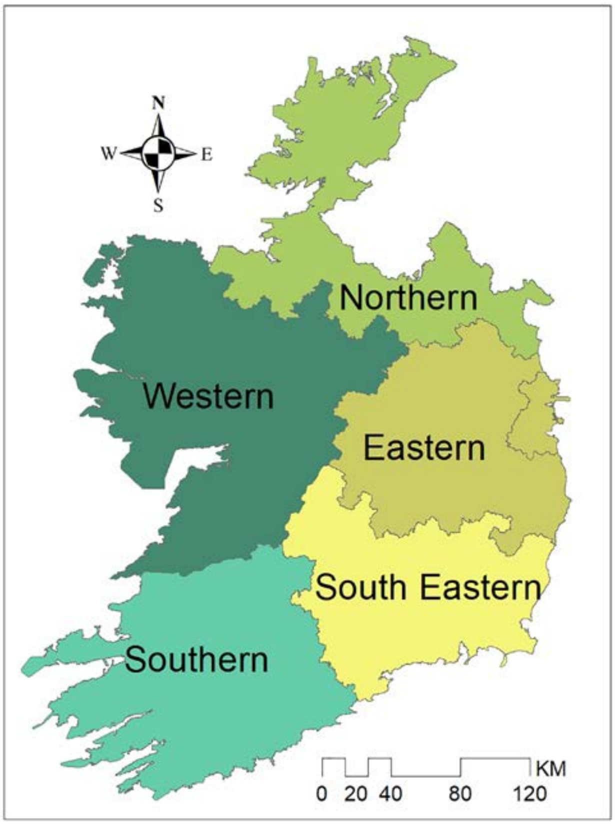


Figure 3.1. Overview of regions used for the assessment of changes in droughts. Reproduced from Meresa and Murphy (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

Table 3.1. EURO-CORDEX data, including GCMs and RCMs used in this study

Code	GCM	RCM	GCM source
CM1	CNRM_CM5	KNMIRACMO22E	Centre National de Recherches Météorologiques, France
CM2	CNRM_CM5	RMIBUGentALARO	Centre National de Recherches Météorologiques, France
CM3	CNRM_CM5	CLMcomCCLM4	Centre National de Recherches Météorologiques, France
CM4	EC_EARTH	KNMIRACMO22E	EC-Earth consortium, Europe
CM5	HadGEM2_ES	KNMIRACMO22E	Met Office Hadley Centre, UK
CM6	HadGEM2_ES	CLMcomCCLM4	Met Office Hadley Centre, UK
CM7	HadGEM2_ES	DMIHIRHAM5	Met Office Hadley Centre, UK
CM8	MPI_ESM_LR	MPICSCREMO2009	Max Planck Institute for Meteorology, Germany
CM9	MPI_ESM_LR	CLMcomCCLM4	Max Planck Institute for Meteorology, Germany
CM10	NorESM1_M	DMIHIRHAM5	Norwegian Earth System Model (NorESM) Climate Modeling Consortium, Norway
CM11	GFDL_ESM2G	GERICSREMO2015	NOAA Geophysical Fluid Dynamics Laboratory, USA

NOAA, National Oceanic and Atmospheric Administration.

for each model/RCP combination were downloaded from the European nodes of the Earth System Grid Federation (ESGF; https://esgf.llnl.gov). Observed gridded daily air temperature and precipitation data at 1 km resolution (Walsh, 2012), available for the period 1976–2005, were used to bias adjust the EURO-CORDEX model outputs. Prior to implementing bias adjustment, observed data were rescaled to match the EURO-CORDEX resolution and then each of the 11 members was adjusted using double gamma quantile mapping for precipitation and empirical quantile matching for temperature. Bias adjustment was implemented at the grid scale, with biases identified during the reference period (1976–2005) used to adjust future climate simulations. Meresa and Murphy (2023) provide full details on bias adjustment methods and results.

3.2.2 *Drought indices*

The Standardised Precipitation Index (SPI) (Mckee *et al*., 1993) and the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al*., 2010) are used to evaluate drought characteristics. Meresa and Murphy (2023) provide the statistical details of how each metric was fitted. For SPEI, PET was estimated from bias-adjusted temperature using the method of Oudin *et al*. (2005). We identify droughts using 3- and 6-month accumulation periods. A threshold of –1 is used to identify drought onset, with termination occurring when SPI/SPEI values return to zero. Drought magnitude was calculated as the sum of all negative values from drought onset to termination (Zhang *et al*., 2018; Spinoni *et al*., 2020). Drought duration is the number of months from onset to termination, with the mean duration for each 30-year period (reference and future) calculated as the sum of all event durations divided by the number of events. Drought frequency refers to the probability of drought occurrence in each 30-year period, estimated as the ratio of the number of months in drought to the total number of months in each 30-year period (i.e. reference and future period).

In addition to individual drought events, we also use SPI and SPEI to assess changes in seasonal drought magnitude. For this purpose, we use SPI/SPEI-3 in February, May, August and November to represent drought conditions in winter, spring, summer and autumn, respectively. Changes in seasonal drought magnitude were examined in two ways: first, by calculating changes in seasonal average SPI/SPEI-3 for reference and future periods, and, second, by examining magnitude changes only for seasons classified as being in drought (i.e. seasonal SPI/SPEI-3 less than –1). For the latter we identify seasons in each 30-year period for which SPI/SPEI was less than –1, then summed these negative values and divided by the number of years classified as in drought. This provides a sense of how the relative magnitude of seasonal drought conditions changes between reference and future periods.

3.3 Changes in Drought Frequency

Changes in drought frequency averaged across the island for each accumulation period (3 and 6 months) were evaluated for the 2080s relative to the reference period, using SPI and SPEI. SPI-3 shows modest changes, with more substantial changes evident for SPEI-3, indicating the importance of evaporative losses in determining future drought frequency. Both RCPs show increasing drought frequency for SPEI-3 by the 2080s; however, climate models show a wide range of change (Figure 3.2). For SPEI-6, again, large differences are evident across climate models, with the ensemble mean indicating greater increases in frequency than for SPI-6.

Figure 3.3 shows the spatial variation of changes in drought frequency from the ensemble mean, with increases in drought frequency for SPI-3 evident in the south and south-west under RCP4.5, and decreases in frequency in the north-east. Again, more substantial changes are evident for SPEI-3, with increases evident for the midlands and east of the island, greatest under RCP8.5. Increases in the frequency of SPI-6 droughts are evident in the south-east and west for RCP4.5, with decreases in the north-east. For the higher emissions pathway (RCP8.5), increases in drought frequency are simulated across the western half of the island, with little change for the eastern seaboard. For SPEI-6 under RCP8.5, increases in frequency are simulated throughout the midlands, east and north of the island.

3.4 Changes in Drought Event Magnitude and Duration

Changes in drought magnitude and duration for each of the five regions analysed are shown in Figure 3.4. For SPI-3, changes in magnitude are modest, with the largest increases typically evident for RCP8.5. Similar results are evident for SPI-3 drought duration, with overall modest increases in duration simulated in each region. More substantial changes emerge for SPEI-3 across all regions, with greatest increases in drought magnitude simulated for the east, south and south-eastern regions. Increases in SPEI-3 drought duration are greatest under RCP8.5 and most evident in the east, south and south-east.

Changes in the magnitude of SPI-6 and SPEI-6 drought events are generally modest, with the ensemble mean for the 2080s comparable to the reference period; however, for both accumulation periods, there is an increase in the upper range of simulations under both RCPs by the end of the

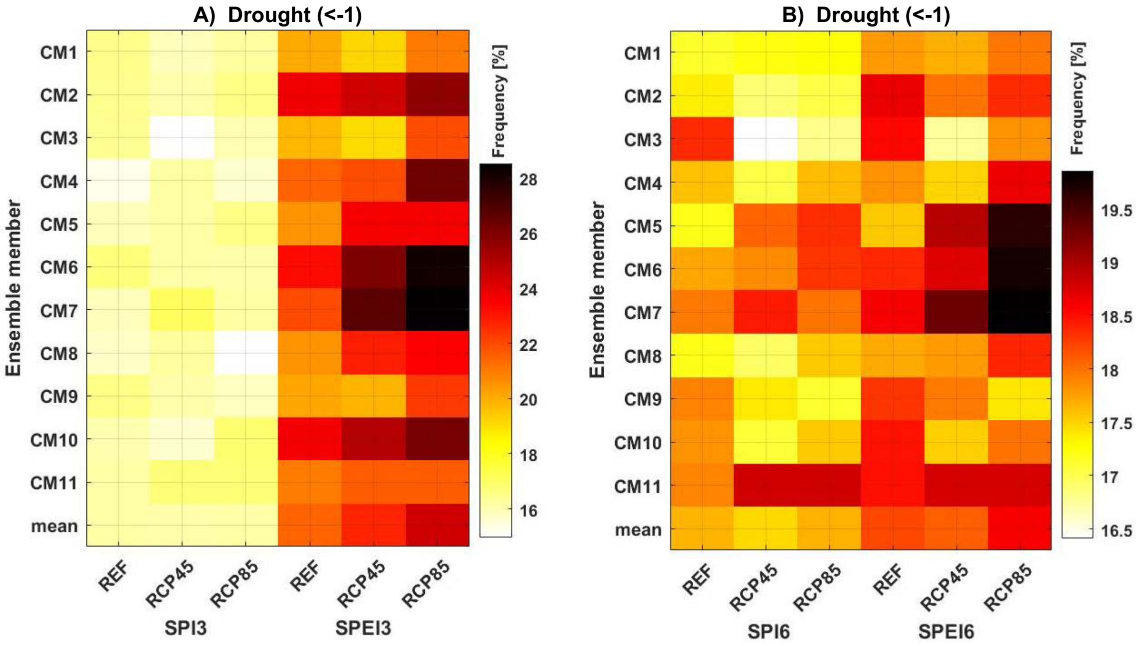


Figure 3.2. Spatially averaged projected changes (percentage) in drought frequency for the island of Ireland using SPI and SPEI at a 3-month accumulation time scale (A) and 6 months (B) for each EURO-CORDEX ensemble member and the ensemble mean for the reference period and each RCP by the 2080s. Reproduced from Meresa and Murphy (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

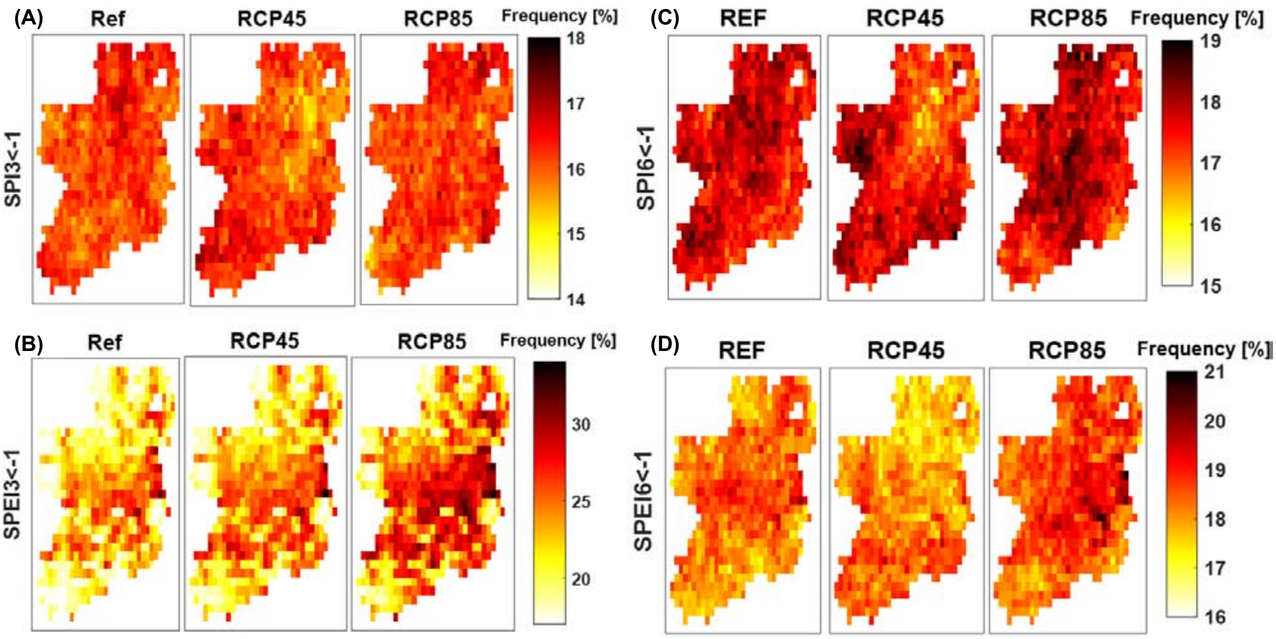


Figure 3.3. Ensemble mean changes in drought frequency (percentage) for SPI-3 (A), SPEI-3 (B), SPI-6 (C) and SPEI-6 (D) for the reference period and each RCP (RCP45 and RCP85) for the 2080s. Reproduced from Meresa and Murphy (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

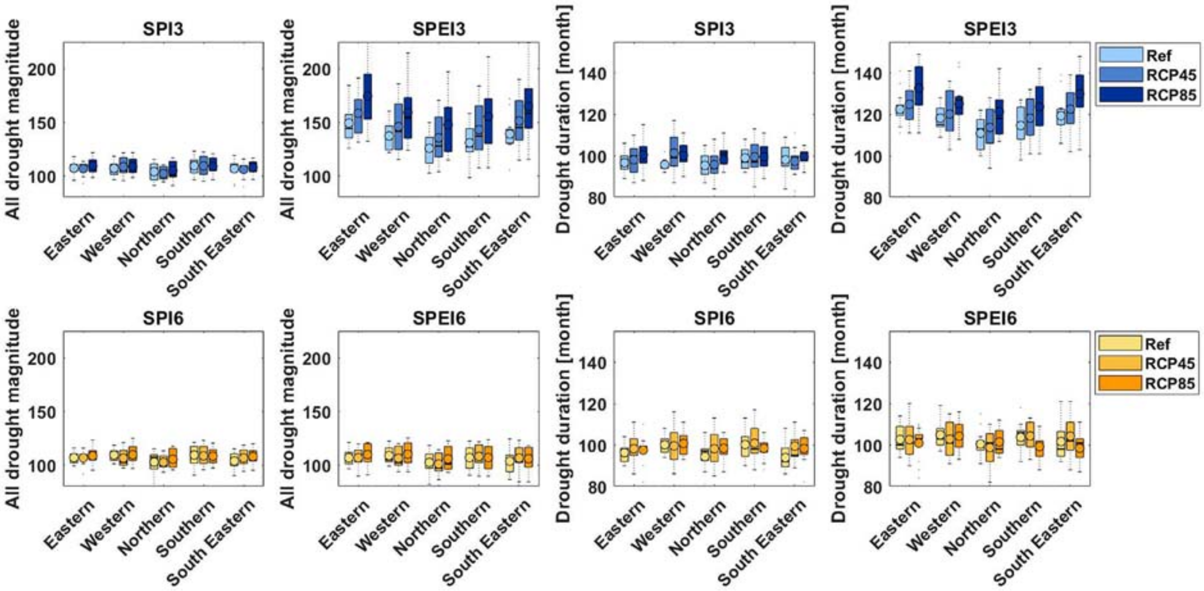


Figure 3.4. Distribution of mean drought magnitude and duration of drought events identified using SPI/SPEI at 3- (blue) and 6-month (orange) accumulation periods for each RCP and region. Each box shows the interquartile range simulated from 11 EURO-CORDEX ensemble members for that region. The circles indicate the ensemble mean, and the horizontal line the median. Reproduced from Meresa and Murphy (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

century. SPI-6 events show modest increases in duration under RCP8.5, greatest in the south-east and north. There are suggestions of modest decreases in duration in the south. For SPEI-6, little change in duration is evident for the ensemble mean in each region; however, the range increases for RCP4.5. For RCP8.5, there is a tendency for decreases in duration of SPEI-6 events in the southern and south-eastern regions. These modest changes and differences between RCPs are probably due to increasing winter rainfall and the signal of that increase being greater in the higher emissions pathway. Notably, the range of changes in both magnitude and duration is greater for SPEI-6, again highlighting the importance of evaporative losses for future drought characteristics.

3.5 Changes in Seasonal Drought Magnitude

Changes in seasonal average drought conditions were assessed for the ensemble mean using SPEI-3 for the last month in each season (i.e. summer is assessed using August SPEI-3), with results presented in Figure 3.5. In winter, increases in SPEI (i.e. decreases in drought) are evident under both emissions pathways, associated with increasing winter precipitation. For spring, decreases in SPEI-3, indicating greater drought magnitude, are evident for the east and south-east of the island, particularly for RCP8.5. Summer shows the most substantial changes, with decreases in SPEI-3 across much of the island, especially for RCP8.5 and the southern half of the island. These changes are consistent with greater temperature increases and, hence, evapotranspiration under the higher emissions pathway. For autumn, changes are modest, with a slight increase in average SPEI values under both emissions scenarios. In spring and summer, decreases in average SPEI-3 values indicate the propensity of increased drought magnitude in these seasons. In winter and autumn, increases in average SPEI-3 suggest decreases in drought propensity, but not that drought magnitude will decrease. We explore changes in seasons categorised as in drought next.

Changes in the magnitude of deficits for seasons characterised as in drought were evaluated using both SPI-3 and SPEI-3. Results are presented for each region in Figure 3.6 for all 11 EURO-CORDEX ensemble members. For winter, decreases in drought magnitude are simulated for all regions under RCP4.5 for both drought metrics. For RCP8.5, increases in both the ensemble mean and upper bound are evident for both SPI-3 and SPEI-3, although

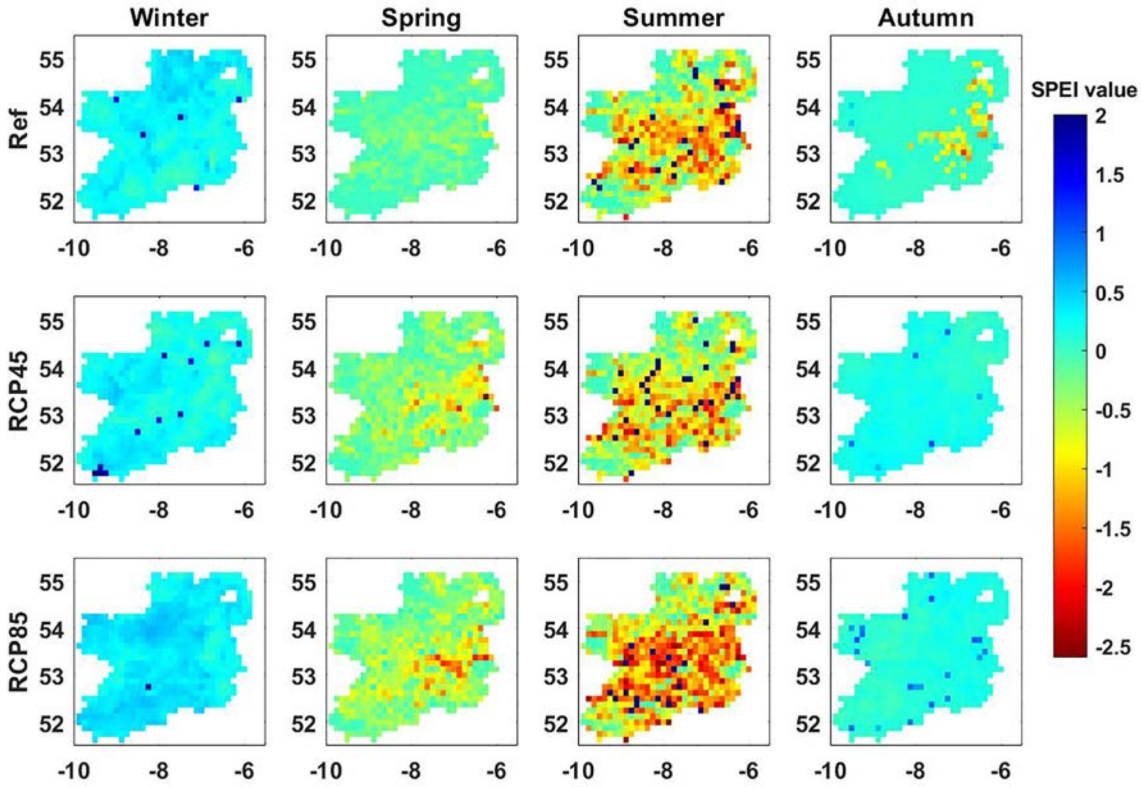


Figure 3.5. Ensemble mean projected changes in seasonal average SPEI values for the reference period and far future (2080s) under RCP4.5 and RCP8.5. Each season is represented by SPEI-3 for the last month of the season (i.e. summer is August SPEI-3). Reproduced from Meresa and Murphy (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

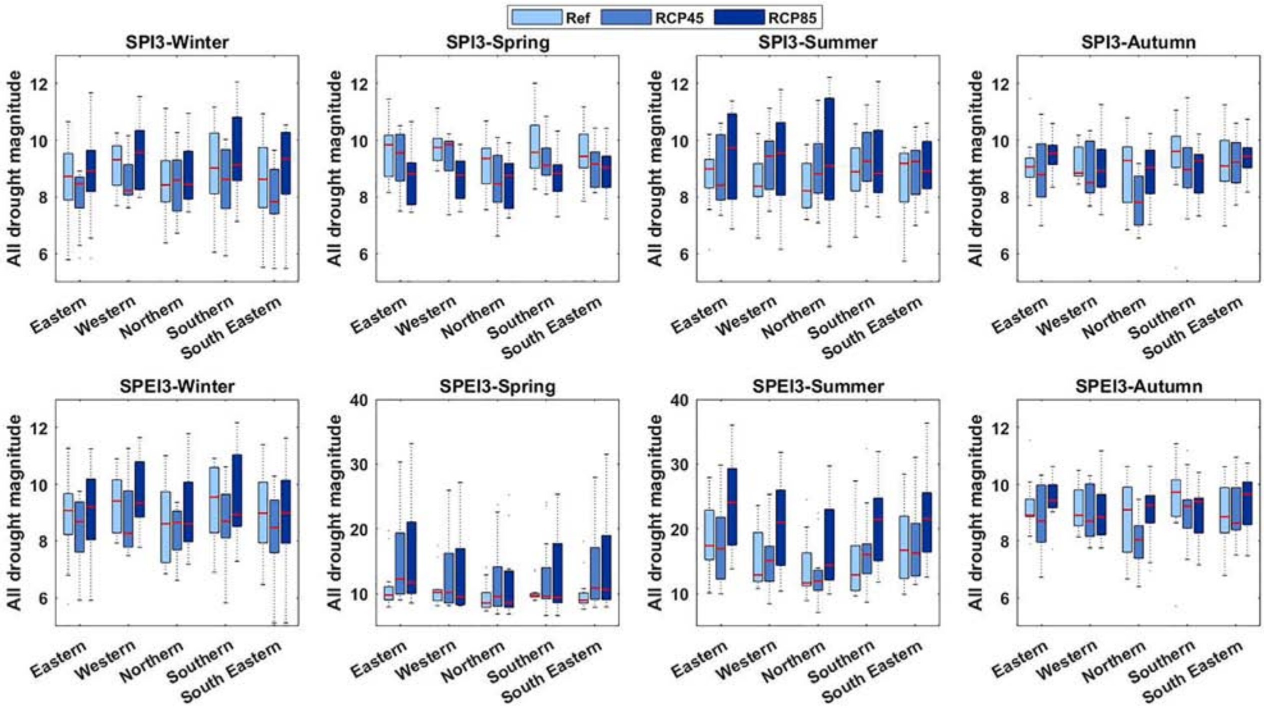


Figure 3.6. Projected changes in seasonal drought magnitude for SPI-3 (top) and SPEI-3 (bottom) for each region. Box plots show the interquartile range simulated from 11 EURO-CORDEX ensemble members for that region. The horizonal lines indicate the ensemble mean. Note the scale differences for spring and summer for SPEI-3. Reproduced from Meresa and Murphy (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

increases are modest relative to summer. For autumn, almost all regions experience a decrease in drought magnitude relative to the reference period for both drought metrics, especially the northern region. The exception is the eastern region, where SPEI-3 shows an increasing autumn drought magnitude for the higher emissions pathway. For spring, the importance of drought metric is very clear. Considering only precipitation deficits, SPI-3 shows a decrease in drought magnitude for all regions. However, by accounting for evapotranspiration losses, SPEI-3 shows substantial increases in drought magnitude in all seasons, especially in the east and for the high-emissions pathway (RCP8.5). The greatest changes in drought magnitude are returned for summer, again notably larger for SPEI-3 and RCP8.5, indicating the importance of emissions reductions for the severity of summer droughts.

3.6 Discussion and Conclusion

Our results indicate a transition to wetter winters and drier summers, with increases in PET losses in summer and late spring months driving increases in spring and summer drought across Ireland. The magnitude of future drought changes is dependent on the emissions pathway, with RCP8.5 returning the most substantial changes. Considerable differences in future droughts depending on the indicator used were also found. For SPI, changes are more moderate than for SPEI, indicating the importance of PET in determining future droughts in spring and summer. This highlights the importance of employing SPEI, rather than SPI, for monitoring current and future drought risk. In addition, given the increased seasonality of precipitation, greater changes are found for 3-month, rather than 6-month, accumulation periods. The largest uncertainty in terms of the direction of change is found for spring and autumn, with consequences for confidence in changes in multi-seasonal droughts. These patterns of change are consistent with previous work assessing climate change impacts on the island with different ensembles of climate models (e.g. Nolan *et al*., 2017; Kay *et al*., 2021; Meresa *et al*., 2022; Murphy *et al*., 2023), which indicate wetter winter and drier summer conditions, more pronounced with higher emissions. Our results are also consistent with a study by

Spinoni *et al*. (2018) that assessed future droughts from the EURO-CORDEX ensemble at the European scale, highlighting increased drought magnitude and frequency in spring and summer, with more modest changes in autumn and decreases in winter in northern Europe.

We find the greatest increases in drought magnitude, frequency and duration in the east and midland regions. Such changes are likely to pose challenges for water management. At present, growing water demand coupled with ageing infrastructure has resulted in a reduced margin and security of water supply for Dublin (Kelly-Quinn *et al*., 2014; Wilby and Murphy, 2018). Continued growth in water demand together with increases in drought frequency and magnitude are likely to further complicate water management in the region. Groundwater also plays an important role in water provision across the island, particularly in the midlands. Decreases in winter drought frequency and magnitude with increased precipitation may increase recharge potential. However, impacts are likely to be moderated by aquifer characteristic (Williams and Lee, 2008; Cantoni *et al*., 2017), and further research is required to better understand how these reported changes may impact on groundwater resources. Irish agriculture is heavily dependent on grass-fed dairy production, with increases in spring and summer droughts likely to impact on grass growth. The drought of 2018 highlighted the vulnerability of the sector to such drought events (Dillon *et al*., 2019; Falzoi *et al*., 2019). Finally, drought in 2018 also resulted in degraded water quality, affecting sensitive riverine species and habitats (Mellander and Jordan, 2021). The impact of future drought changes on water quality is poorly understood.

4 Drought Characteristics and Propagation at the Catchment Scale

4.1 Introduction

While Chapter 3 examined changes in meteorological drought across the island, this chapter seeks to understand how drought is likely to change at the catchment scale and investigates potential changes in drought propagation. At the catchment scale, drought propagation concerns how meteorological deficits are transferred to deficits in river flow, with propagation typically controlled by hydrological processes that operate at different scales, together with catchment characteristics (e.g. groundwater storage, soil and land use characteristics) (Ganguli *et al*., 2022; Sutanto and Van Lanen, 2022). For selected catchments, we employ standardised drought indices to examine changes in meteorological drought (precipitation and moisture deficits (precipitation minus PET)) and hydrological drought (runoff and baseflow), together with changes in the likelihood of meteorological drought propagating to hydrological drought conditions. Internationally, few studies have employed multiple metrics in this way to understand changes in drought characteristics and their propagation at the catchment scale (Zhou *et al*., 2021). To achieve these aims we employ 12 GCMs from the CMIP6 (Eyring *et al*., 2016), forced with SSP370. Following bias adjustment, these scenarios are used to force the SMART hydrological model for each catchment. To evaluate changes in drought and their propagation, we fit standardised indices (SPI, SPEI, Standardised Runoff Index (SSI), Standardised Baseflow Index (SBI)) at 3-, 6- and 12-month aggregation timescales. Full details of the analysis have been published by Meresa *et al*. (2023); only an overview of key findings is provided here.

4.2 Catchments, Data and Methods

4.2.1 Catchment and climate data

Ten catchments from across Ireland with different hydroclimatic characteristics were selected for analysis (Table 4.1). Each catchment has good-quality discharge and meteorological and hydrological data, and limited impact from urbanisation, land use change and abstractions of water resources (Murphy *et al*., 2013). Daily temperature and precipitation data for the period 1976–2005 were obtained from Met Éireann and catchment average series derived for each catchment. The temperature-based method of Oudin *et al*. (2005) was used to derive PET. Daily discharge data were obtained from the Environmental Protection Agency and Office of Public Works for the same period.

Output from 12 CMIP6 climate models (see Chapter 2, Table 2.1), comprising daily air temperature and precipitation data (Table 2.1), forced using the SSP

Table 4.1. Catchments selected for analysis together with catchment area and Base Flow Index (indicative of groundwater storage)

Gauge number	Station name	Catchment	Area (km^2)	Base Flow Index
06013	Charleville	Dee	309	0.67
12001	Scarrawalsh	Slaney	1031	0.70
14007	Derrybrock	Stradbally	115	0.73
15003	Dinin Bridge	Dinin	140	0.53
18050	Duarrigle	Blackwater	250	0.48
22035	Laune Bridge	Laune	560	0.68
23002	Listowel	Feale	647	0.52
25001	Annacotty	Mulkear	648	0.64
26029	Dowra	Shannon	117	0.39
33001	Glenamoy	Glenamoy	76	0.43

SSP370 were extracted from the ESGF (website (https://esgf-node.llnl.gov/search/cmip6/) for the period 1976–2100. The land-based grid cell closest to each catchment centroid was used to extract data for each catchment. Bias adjustment was undertaken using the same methods as reported in Chapter 2 (see also Meresa *et al*. (2023) for details on evaluation of bias adjustment methods for assessing drought), and, for observations, the method of Oudin *et al*. (2005) was used to estimate PET from projected temperature series. The SMART hydrological model (Mockler *et al*., 2016; Hallouin *et al*., 2020) was used to simulate river flow, with the model calibrated for the period 1990–2007 and validated for the period 2008–2015. The same approach as described in Chapter 2 was undertaken for calibration/validation, with changes in future drought conditions assessed using the median simulation from 150 parameter sets.

4.2.2 Drought indices

Four drought indices were derived for each catchment, namely the SPI (Mckee *et al*., 1993), SPEI (Vicente-Serrano, *et al*., 2010), SSI (Shukla and Wood, 2008) and SBI. Baseflow is the sum of shallow and deep subsurface flow that sustains river discharge between periods of excess precipitation. The separation of streamflow into surface runoff and baseflow was implemented by applying an automatic baseflow filtering technique to daily streamflow time series (Bosch *et al*., 2017; see also Meresa *et al*., 2023). Each drought index was fitted during the reference period (1976–2005) and then used to evaluate changes in drought for three future time periods: the 2020s (2010–2039), the 2050s (2040–2069) and the 2080s (2070–2099). Droughts were assessed for three accumulation periods (3, 6 and 12 months) using running sums for precipitation and moisture deficits (SPI and SPEI, respectively) and averages for runoff and baseflow (SSI and SBI, respectively). Changes in drought magnitude (severity) and frequency were assessed using the definitions for both outlined in Chapter 3.

4.2.3 Drought propagation

Drought propagation considers the transfer of meteorological deficits to different parts of the catchment system (i.e. soil moisture, runoff and/or groundwater) (Eltahir and Yeh, 1999). Drought propagation was assessed using conditional probabilities (Pontes Filho *et al*., 2019; Ribeiro *et al*., 2019), for example the probability of SPI drought propagating to SSI and SBI. For two drought indices (e.g. SPI and SSI) and their lag time (averaged for all droughts identified in each 30-year period), we used the posterior and prior pairs of probabilities to examine changes in the likelihood of propagation (see Meresa *et al*. (2023) for full methodological details). Propagation likelihood was assessed for droughts identified at 3- and 12-month accumulation timescales for both reference and projected future periods using the ensemble mean of projected changes.

4.3 Results

Percentage changes in monthly precipitation, moisture deficits, runoff and baseflow for each future period as simulated by the SMART model forced by our bias-adjusted 12-member ensemble are shown in Figure 4.1. Large decreases in summer for each variable are evident, becoming larger as the century progresses. While considerable ranges of change are evident, summer precipitation shows a mean reduction of ≈6% across the 10 catchments for the 2020s, ≈17% by the 2050s and ≈40% by the 2080s. Concurrent increases in evaporative demand result in increases in summer soil moisture deficits of greater magnitude than reductions in precipitation alone. Large summer decreases in runoff and baseflow are also simulated. The largest decreases are noted for baseflow, with mean reductions across catchments ranging from ≈10% in the 2020s to ≈50% in the 2080s. Outside summer, winter (December, January, February) precipitation shows a tendency for increases, becoming progressively larger as the century progresses, while the direction of change in spring (March, April, May) and autumn (September, October, November) precipitation is uncertain. Similar changes are evident for runoff and baseflow.

Figure 4.2 shows the relative changes in seasonal and annual drought magnitude and frequency for all indices for each catchment for the 2050s and 2080s. While box plots show a wide range of change, there is a tendency for decreased drought magnitude in all seasons except summer in most catchments. In summer, SPI drought magnitude and frequency are projected to increase by ≈50% and ≈20%, respectively, in the 2050s and by a further ≈10% by

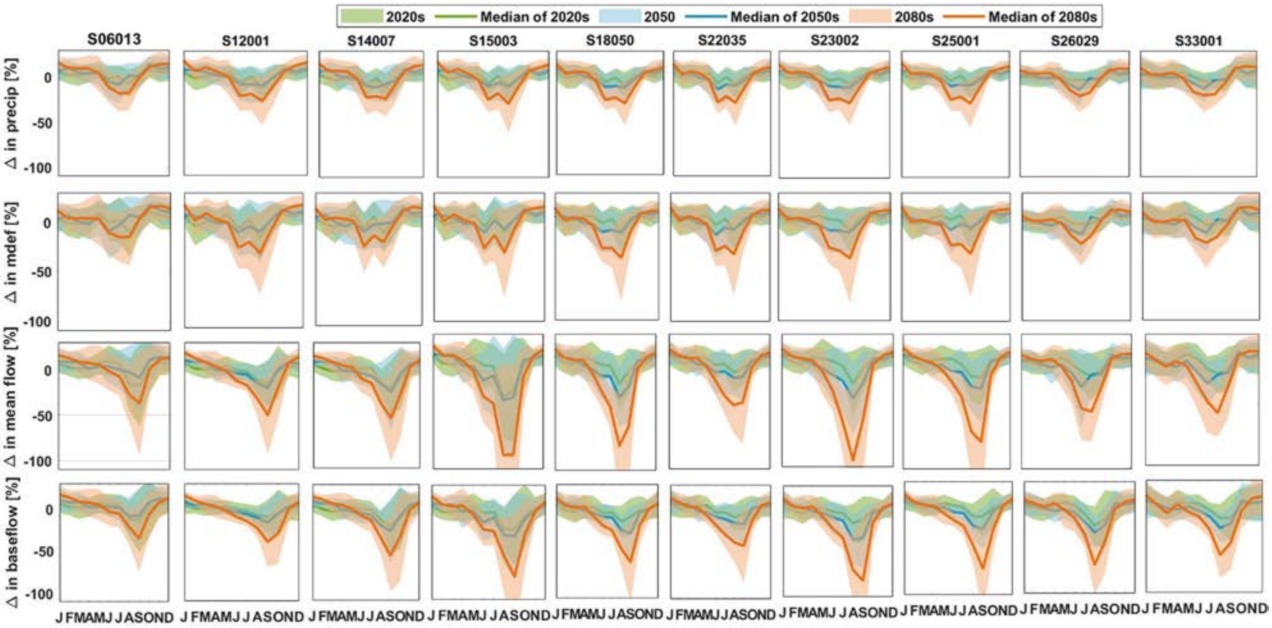


Figure 4.1. Changes (%) in precipitation (first row), mean moisture deficit (second row), mean runoff (third row) and mean baseflow (last row) in the 2020s (green shaded and green solid line), the 2050s (blue shaded and blue solid line) and the 2080s (orange shaded and orange solid line) for each catchment with respect to the reference period (1976–2005) under SSP370. The shaded area and line show, respectively, the spread and ensemble median from 12 bias-adjusted CMIP6 climate models. Reproduced from Meresa *et al*. (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

the 2080s across catchments. Hydrological indices (SSI and SBI) also show increasing summer drought magnitude and frequency by the 2050s and 2080s. Notably, SPI and SPEI show a lower spread than SSI and SBI, indicating the greater uncertainty in future projections of hydrological drought. Individual catchments show only modest differences in drought changes. In the 2050s, the Annacotty, Dowra and Glenamoy catchments show smaller changes in drought magnitude and frequency during summer and spring. In the 2080s, changes typically become progressively greater across catchments, except for the Stradbally and Dee catchments, which show a decrease in summer drought magnitude and frequency for the 2080s relative to the 2050s.

Changes in the likelihood of meteorological to hydrological drought propagation in each catchment was assessed for 3- and 12-month accumulation periods. Figure 4.3 shows results for the reference and future time periods. For future periods (2020s, 2050s, 2080s), the probability of drought propagation increased slightly. Largest increases are found for the 2050s in the Dee, which shows a 7% increase in the probability of SPI-3 drought propagating to SSI drought. Changes in probability of <5% are found for other catchments. Similar results are found for the propagation of SPI-3 to SBI droughts. Overall changes in drought propagation for 3-month accumulations are modest.

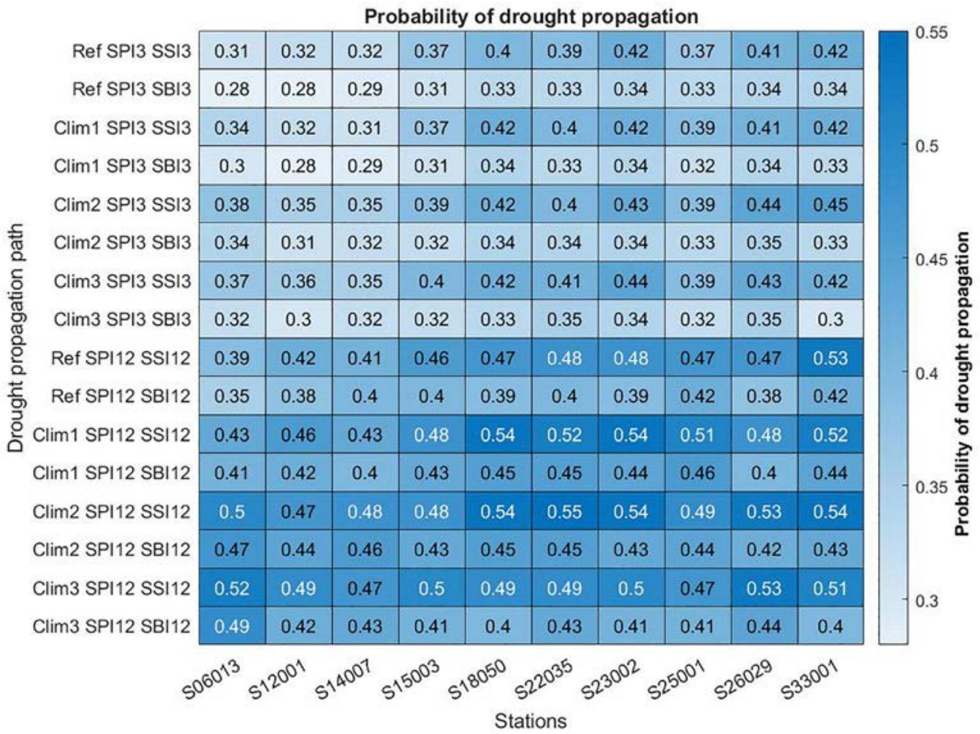
For the 12-month accumulation period, the probability of SPI-12 propagation to SSI ranges from 0.39 (Dee) to 0.53 (Glenamoy) during the reference period. The Blackwater and Feale catchments show, respectively, a 7% and 6% increase in the probability of drought propagation from SPI-12 to SSI for the 2020s. For the 2050s, the Dee shows increases of 11% and 13%, relative to the reference period. Other catchments tend to show increases in SPI to SSI propagation probability, but typically of less than 10% during the 2050s and 2080s. The largest increases are found for SPI to SBI propagation probabilities. During the reference period, propagation of meteorological to groundwater drought is smallest for the Dee (0.35) and largest for the Stradbally and Dinin (0.40) catchments. For the 2020s, catchments showing more than a 10% increase in propagation probability include

Figure 4.2. Change (%) in seasonal and annual drought magnitude (top) and frequency (bottom) in the 2050s (left: 2040–2069) and 2080s (right: 2070–2099) for each catchment using the SPI, SPEI, SSI and SBI under SSP370. Box plots show the spread of 12 climate models bias adjusted using double gamma quantile mapping. Box plots show the median and interquartile range (IQR) of simulated changes with black dots indicating changes outside the IQR. Reproduced from Meresa *et al*. (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

Dee (14%) and Stradbally (10%). By the 2050s, all catchments show an increase in probability, greatest for the Dee (19%), Stradbally (15%) and Slaney (11%) catchments. Increases in the probability of drought propagation from SPI to SBI are not as high for the 2080s, indicating the importance of increases in winter and spring precipitation in offsetting drought propagation to baseflow.

4.4 Discussion and Conclusion

The results indicate substantial changes in monthly/seasonal precipitation that drive changes in drought



Drought propagation path	S06013	S12001	S14007	S15003	S18050	S22035	S23002	S25001	S26029	S33001
Ref SPI3 SSI3	0.31	0.32	0.32	0.37	0.4	0.39	0.42	0.37	0.41	0.42
Ref SPI3 SBI3	0.28	0.28	0.29	0.31	0.33	0.33	0.34	0.33	0.34	0.34
Clim1 SPI3 SSI3	0.34	0.32	0.31	0.37	0.42	0.4	0.42	0.39	0.41	0.42
Clim1 SPI3 SBI3	0.3	0.28	0.29	0.31	0.34	0.33	0.34	0.32	0.34	0.33
Clim2 SPI3 SSI3	0.38	0.35	0.35	0.39	0.42	0.4	0.43	0.39	0.44	0.45
Clim2 SPI3 SBI3	0.34	0.31	0.32	0.32	0.34	0.34	0.34	0.33	0.35	0.33
Clim3 SPI3 SSI3	0.37	0.36	0.35	0.4	0.42	0.41	0.44	0.39	0.43	0.42
Clim3 SPI3 SBI3	0.32	0.3	0.32	0.32	0.33	0.35	0.34	0.32	0.35	0.3
Ref SPI12 SSI12	0.39	0.42	0.41	0.46	0.47	0.48	0.48	0.47	0.47	0.53
Ref SPI12 SBI12	0.35	0.38	0.4	0.4	0.39	0.4	0.39	0.42	0.38	0.42
Clim1 SPI12 SSI12	0.43	0.46	0.43	0.48	0.54	0.52	0.54	0.51	0.48	0.52
Clim1 SPI12 SBI12	0.41	0.42	0.4	0.43	0.45	0.45	0.44	0.46	0.4	0.44
Clim2 SPI12 SSI12	0.5	0.47	0.48	0.48	0.54	0.55	0.54	0.49	0.53	0.54
Clim2 SPI12 SBI12	0.47	0.44	0.46	0.43	0.45	0.45	0.43	0.44	0.42	0.43
Clim3 SPI12 SSI12	0.52	0.49	0.47	0.5	0.49	0.49	0.5	0.47	0.53	0.51
Clim3 SPI12 SBI12	0.49	0.42	0.43	0.41	0.4	0.43	0.41	0.41	0.44	0.4

Figure 4.3. Changes in the probability of meteorological to hydrological drought propagation in each catchment assessed for 3- and 12-month accumulation periods for the reference period, clim1 (2020s), clim2 (2050s) and clim3 (2080s) from the median simulation of 12 CMIP6 GCMs forced by SSP370. Reproduced from Meresa *et al*. (2023); licensed under CC BY-NC-ND 4.0 DEED (https://creativecommons.org/licenses/by-nc-nd/4.0/).

magnitude and frequency in each catchment. Ranges of change are large and span a sign change, but summer (June, July, August) precipitation shows large reductions (ensemble mean reduction across catchments of −40% by the 2080s), with decreases becoming progressively larger as the century progresses. Summer (August 3-month accumulation) shows large increases in the magnitude and frequency of drought in all components of the hydrological system (SPI, SPEI, SSI, SBI) by mid-century. The projected changes in precipitation are similar to those found for a larger sample of catchments by Meresa *et al*. (2022) using the same ensemble, and by Murphy *et al*. (2023) using the EURO-CORDEX and Irish Centre for High-End Computing ensembles (Nolan and Flanagan, 2020). Therefore, the key season for changes in drought is summer, with changes in precipitation for winter and spring months setting antecedent conditions in relation to catchment wetness and groundwater storage.

Modest changes in the likelihood of meteorological drought propagation to hydrological drought events were found for the 3-month accumulation period. For 12-month accumulations, all catchments show an increase in propagation probability by mid-century, with some catchments showing an increase of > 10%. The largest increases in the probability of drought propagation from meteorological to hydrological events were found for catchments where groundwater storage is limited. We find that, for catchments with substantial groundwater storage, increases in winter and spring precipitation by the 2080s can result in a decrease in the likelihood of drought propagation from precipitation to baseflow, indicating the importance of intra-seasonal changes in precipitation and groundwater characteristics in drought dynamics. Notably, summer hydrological drought (SSI and SBI) simulations show larger ranges of change than meteorological drought (SPI and SPEI), indicating the non-linear translation of meteorological to hydrological drought and the additional uncertainty associated with hydrological modelling (Meresa and Zhang, 2021). Future research could attempt to constrain hydrological model calibration using additional data such as groundwater recharge, in addition to observed discharge, to select parameter sets (e.g. Mockler *et al*., 2016).

Such changes in drought dynamics, together with the magnitude and frequency of events, could have substantial management implications for Irish water resources and agriculture. Changes in droughts should therefore be central to adaptation planning across sensitive sectors. Even in the absence of climate change, existing vulnerability was evidenced by drought conditions in 2018, with widespread water shortages, hosepipe bans and challenges for grass growth in a pasture-based agricultural system, indicating an adaptation deficit (Falzoi *et al*., 2019). To assist in adaptation planning, Jobbová *et al*. (forthcoming) provide a database of drought impacts associated with historical droughts across the island that could be employed to examine changing vulnerability to droughts. O'Connor *et al*. (2023) link impacts reported in newspaper articles to thresholds in standardised drought indices to better inform drought monitoring and warning at the catchment scale.

Finally, it is important to note that our analysis of drought assumes no changes in land use in each catchment, and this is unlikely to be the case. Land use change through afforestation, rewetting and other interventions is likely to result from greenhouse gas mitigation strategies. Implemented on large scales, such strategies are likely to influence drought risk. Some studies show that vegetation change, through the partitioning of green (water use by vegetation) and blue water (discharge), can have significant implications for increasing hydrological drought risk at the catchment scale (e.g. Vicente-Serrano *et al*., 2021; Peña-Angulo *et al*., 2022). Future research should examine scenarios of climate and land use change and their combined impact on droughts.

5 Conclusions and Recommendations

HydroPredict aimed to develop simulations of hydrological response under climate change to inform climate change adaptation planning in Ireland. The project incorporated key uncertainties in future projections of low flows and droughts by employing an ensemble of climate models from CMIP6 forced by three SSPs (SSP126, SSP370 and SSP585) to model changes in hydrological response across 37 catchments. The impact assessment considered uncertainties from climate models, emissions pathways, bias adjustment approaches and hydrological models to provide water managers with ranges of change in policy-relevant metrics for future time periods. It also assessed future changes in meteorological drought characteristics using regionally downscaled climate model projections from the EURO-CORDEX ensemble forced by two RCPs. Standardised drought indicators were used to quantify changes in drought frequency, magnitude and duration for the 2080s relative to the present.

Projected changes in seasonal and mean flows across catchments showed a wide range of outcomes. While the direction of change in mean flows for most seasons is uncertain, there are strong indications of increased winter flows and decreased summer flows. These findings align with previous studies and simulations driven by regional climate projections in Northern Ireland. These projected changes have significant implications for water resources management, freshwater ecosystems and water quality in Ireland, particularly under higher emissions scenarios (SSP370 and SSP585) by mid-century and the end of the century. Substantial reductions in low flows are also expected, which will pose challenges for various sectors. However, reducing greenhouse gas emissions, as represented by SSP126, can mitigate the magnitude of reductions in summer flows and low flows compared with more fossil fuel-intensive scenarios.

Two hydrological models, SMART and GR4J, yielded different simulation results. The SMART model showed greater increases in winter flows and the GR4J model demonstrated larger decreases in summer flows and low flows. Both models performed well during verification, highlighting the importance of including different model structures in climate change impact assessments. The projected changes in seasonal mean flows and annual low flows presented in this study are valuable for informing adaptation strategies in the water sector, including water resource management, water quality assessment and freshwater ecosystem management. In employing these results to inform adaptation, decision-makers should consider the full range of changes presented. While the results presented here sample a large portion of the modelling chain, they are limited to the models and methods employed and do not represent the full plausible range of change. This should be borne in mind when developing robust adaptation responses. These results can also contribute to the development of storylines for adaptation planning and stress testing of adaptation options. Future work could expand the analysis to include more catchments and explore how catchment characteristics influence the response to climate change. In addition, an emulator of climate change impacts could be developed based on the results, allowing for a broader exploration of uncertainty and providing insights for ungauged catchments where observations are lacking.

Regarding meteorological droughts, the results from the EURO-CORDEX ensemble indicated a transition to wetter winters and drier summers in Ireland. Increases in PET losses during summer and late spring months were found to be key in driving increases in spring and summer drought across the country. The magnitude of future drought changes depended on the emissions pathway, with the higher emissions RCP8.5 scenario showing the most substantial changes. Different drought indicators yielded considerable differences in future drought projections, indicating the importance of including both PET losses and precipitation changes in assessments of future drought. These findings highlight the importance of using metrics such as the SPEI, rather than the SPI, for monitoring current and future drought risk, particularly in spring and summer. The impact of increased precipitation seasonality was also observed, with larger changes in drought characteristics found for seasonal droughts (3-month accumulation periods) than for inter-seasonal droughts (6-month accumulation periods).

The study found that the east and midland regions would experience the greatest increases in drought magnitude, frequency and duration, posing challenges for water management. Water supply for Dublin, which already faces challenges due to growing demand and ageing infrastructure, would be further complicated by increased drought frequency and magnitude. Groundwater, important for water provision across the island, may experience increased recharge potential due to decreased winter drought frequency and magnitude. However, the impact would depend on aquifer characteristics, requiring further research. The agricultural sector, heavily dependent on grass-fed dairy production, would be impacted by increases in spring and summer droughts affecting grass growth. Such changes in drought events may also pose challenges for water quality, impacting sensitive riverine species and habitats. The consequences of future drought changes in terms of water quality remain poorly understood.

Lastly, the project aimed to understand how changes in meteorological droughts propagate through the catchment system to impact river flows and groundwater. In-depth evaluation of a smaller number of catchments was conducted to analyse the relationship between meteorological deficits, soil moisture, river flow and groundwater deficits, and how the likelihood of propagation between different components of the hydrological system may change in the future.

The study showed substantial changes in monthly/seasonal precipitation, driving changes in drought magnitude and frequency in each catchment. Summer precipitation exhibited significant reductions, with progressively larger decreases expected as the century progresses. Mid-century projections indicated large increases in the magnitude and frequency of summer drought in all components of the hydrological system, highlighting summer as the key season for changes in drought. Changes in winter and spring precipitation are important in setting antecedent conditions for catchment wetness and groundwater storage. For catchments with high groundwater storage, the ensemble mean indicates decreased drought duration, likely because of increases of winter and spring precipitation. These findings highlight the susceptibility to multi-year droughts, whereby a dry winter/spring increases the risk of extreme droughts, given the large-scale summer drying indicated by the ensemble mean.

By mid-century, all catchments showed an increase in the probability of drought propagation from meteorological to hydrological drought, with some catchments experiencing an increase of > 10%. Catchments with limited groundwater storage showed the largest increases in the probability of drought propagation. Interestingly, catchments with substantial groundwater storage could experience a decrease in the likelihood of drought propagation from precipitation to baseflow, given projected increases in winter and spring precipitation by the 2080s. This highlights the importance of intra-seasonal changes in precipitation and groundwater characteristics in drought dynamics. Summer hydrological drought simulations exhibited larger ranges of change than meteorological drought, indicating the additional uncertainty associated with hydrological modelling.

Given the substantial changes in seasonal mean and low flows and the magnitude, frequency and duration of droughts found across this study, adaptation planning for sensitive sectors such as water resources, agriculture and ecosystems should prioritise changes in droughts. Existing vulnerability is abundantly evident from the recent 2018 drought, which caused water shortages, hosepipe bans and challenges for grass growth, and degradation in water quality. Databases of historical drought impacts and thresholds in standardised drought indices could assist in examining changing vulnerability and informing drought monitoring and warning at the catchment scale.

Finally, this study assumes no changes in land use, which is unlikely to be the case. Land use changes, driven by greenhouse gas mitigation strategies such as afforestation and rewilding, can influence drought risk. Vegetation change could have significant implications for increasing hydrological drought risk at the catchment scale through increasing water losses. Future research should examine scenarios of climate and land use change and their combined impact on droughts.

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Abbreviations

CI	Confidence interval
CMIP6	Coupled Model Intercomparison Project Phase 6
ESGF	Earth System Grid Federation
GCM	Global climate model
GR4J	Génie Rural à 4 paramètres Journalier
PET	Potential evapotranspiration
RCM	Regional climate model
RCP	Representative Concentration Pathway
SBI	Standardised Baseflow Index
SMART	Soil Moisture Accounting and Routing for Transport
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SSI	Standardised Runoff Index
SSP	Shared socioeconomic pathway

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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