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# HydroDARE: Detection and Attribution of Change in Hydrological Series

Authors: Conor Murphy, Saoirse Fordham, Mohamed Bile and Sean Donegan

Lead organisation: ICARUS Climate Research Centre, Department of Geography, Maynooth University



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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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## What did the research aim to address?

HydroDARE, co-funded by Met Éireann, aimed to address a key knowledge gap in Irish climate adaptation: how to tell whether observed changes in floods, droughts and rainfall extremes are caused by human-driven climate change, natural variability, catchment change or data issues. This matters because flood risk management, water resource planning, agriculture, infrastructure design and local adaptation all depend on understanding why hydrological risk is changing. The project developed a practical, modular framework for detecting, attributing and scaling changes in hydrologically relevant series under real-world Irish data conditions. Its innovation was to use causal chains linking global warming to local rainfall, evaporative demand and river flow impacts, while explicitly considering uncertainty, internal catchment change, monitoring quality and natural variability. The framework was tested through four policy-relevant case studies covering seasonal rainfall extremes, Shannon floods, drought in Wexford and Storm Babet flooding in Midleton.

## What did the research find?

The research found that human-driven climate change is already affecting important components of hydrological risk in Ireland. Long-term rainfall records show emerging climate change signals in flood-generating rainfall, including increasing winter and spring multi-day rainfall in western Ireland and increasing summer and autumn rainfall intensity in the south-east. In the Shannon catchment, observed increases in annual maximum flood flows are mainly climate driven, with peak flow sensitivity estimated at about 7.5–18.1% per 1°C of global warming, depending on catchment characteristics; arterial drainage may amplify this signal. For drought, no clear climate signal was detected in precipitation-only indicators, but warming-driven evaporative demand is already increasing drought severity. The Midleton case study showed how Storm Babet-type flooding could be stress-tested under further warming. Overall, the HydroDARE findings indicate that hydrological extremes in Ireland are already departing from assumptions of historical stationarity.

## How can the research findings be used?

The findings can be used by the EPA, Office of Public Works, Met Éireann, local authorities, water managers and adaptation practitioners to move from assuming stationarity to monitoring, explaining and stress-testing changing hydrological risk. To support this transition, HydroDARE provides a transferable national framework for climate attribution in hydrology that can be applied across catchments, sectors and future adaptation assessments. The framework can inform flood risk assessment, drought monitoring, infrastructure design, catchment management, climate services and local or sectoral adaptation plans by identifying which variables carry a climate change signal and how they may scale with additional warming. Immediate next steps are to apply the framework more widely across Ireland, integrate flood-generating rainfall and evaporative-demand indicators into monitoring systems, and use event-based counterfactuals to test adaptation pathways, tipping points and design allowances. Implementation will require continued investment in long-term rainfall, temperature and flow monitoring, data rescue, quality assurance and metadata. Further work should extend the approach to ungauged catchments, compound events, heat, interactions with arterial drainage and methods such as UNSEEN to better represent rare but plausible extremes and natural variability.

Project code: 2022-CE-1132

EPA RESEARCH PROGRAMME 2021–2030

# HydroDARE: Detection and Attribution of Change in Hydrological Series

## (2022-CE-1132)

## EPA Research Report

Independent scientific research funded by the Environmental Protection Agency

Prepared by

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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

The HydroDARE project sought to strengthen approaches for the detection and attribution of change in hydrological series. Attribution is central to resilient catchment management and climate adaptation because making decisions on floods, droughts and water resources implicitly assumes a cause of observed change. In rivers and catchments, however, similar changes can arise for very different reasons, including natural climate variability and anthropogenic climate change, and changes in land use and land management, arterial drainage, river engineering and monitoring practice. The HydroDARE project aimed to address these difficulties in distinguishing between potential reasons for change by developing a practical modular framework for the detection, attribution and scaling of change in hydrologically relevant variables, designed to work under real-world Irish conditions and with the available data. The framework uses causal chains to link large-scale climate drivers to local hydrological outcomes, while explicitly accounting for uncertainty, internal catchment change and data quality. A key advantage of the framework is that, where a robust climate change signal is identified, the framework can be used to scale observed changes based on projected warming scenarios and therefore extend the attribution of change to the counterfactual analysis of damaging events.

In this report, various uses of the framework are demonstrated through four policy-relevant Irish case studies. First, use of the framework in the analysis of long-term rainfall observations shows that climate change signals in seasonal rainfall extremes have already emerged beyond historical variability in parts of Ireland. The clearest signals are found in increasing winter and spring multi-day rainfall totals in western Ireland and increasing summer and autumn rainfall intensity in the south-east, indicating that flood-relevant rainfall hazards are already increasing. Therefore, planning assumptions based on historical stationarity may no longer be appropriate. Second, application of the framework to analyse annual maximum flood magnitude in the Shannon catchment shows that observed increases in flood magnitude are predominantly climate driven, mainly through changes in heavy rainfall altering both antecedent and flood-generating conditions, with median increases in annual maximum flood magnitude of approximately 7.5–30% per 1°C increase in global mean surface temperature being seen, depending on catchment characteristics. The evidence also suggests that historical arterial drainage may amplify flood sensitivity to climate change. Third, application of the framework to analyse drought shows a clear climate change signal for drought severity in increased evaporative demand, meaning that warming is already intensifying drought severity even though rainfall trends appear to be explained largely by natural climate variability and the link between these trends and anthropogenic climate change remains uncertain. The drought case study also shows that climate change and natural variability can act together to amplify impacts, with reduced summer rainfall due to natural variability and higher evaporative losses due to warming combining to worsen drought risk. Finally, the Midleton/Storm Babet case study shows how use of the framework can be extended from attribution to event-based counterfactual analysis. This case study shows how a real-life, damaging flood can be considered in a climate change context of additional warming. Using the framework, it is estimated that a Storm Babet-type flood event in Midleton would be around 2.3%, 4.5% or 9.1% greater in magnitude under conditions of 0.5°C, 1.0°C or 2.0°C of additional warming, respectively, and under antecedent conditions similar to those seen during Storm Babet.

Overall, the HydroDARE project has shown that human-driven climate change is already affecting important components of hydrological risk in Ireland, particularly through heavier flood-generating rainfall and increasing atmospheric evaporative demand. At the same time, the project has shown that natural variability and internal catchment change remain essential to understanding observed impacts. The framework developed is rapid to deploy where suitable data exist, and the case study workflows are available for reuse. The project has also highlighted

the critical importance of long-term monitoring, data rescue and quality assurance as foundations for climate adaptation and catchment management. Key priorities for future work include extending the use of the framework to island-wide applications, applying it to other extremes such as heat and compound events, developing it for use in identifying adaptation tipping points and pathways, and pairing it with approaches that would enable the better characterisation of natural variability and rare but plausible extremes.

# 1 Introduction and Framework

Attribution is central to resilient, sustainable catchment management and climate change adaptation, because management decision-making implicitly assumes a *cause* of an observed change (Merz *et al*., 2012; Harrigan *et al*., 2014; Slater *et al*., 2021). Attribution means moving beyond simply showing that change has happened to explaining *why* it has happened. This is especially important for rivers because streamflow is determined by a combination of catchment inputs (e.g. rainfall) and internal catchment processes, and it can reflect many influences acting together (Scussolini *et al*., 2024). Weather and climate are part of the story, but so too are land use and land management, drainage, river engineering, abstractions and discharges, and groundwater–surface water interactions, among other factors. Because so many factors can shape hydrological responses, similar changes can arise for very different reasons. For example, a drop in summer low flows could be driven by hotter, drier conditions that increase water loss from soils and vegetation, or it could reflect rising water demand, increased land drainage, forestry expansion or changes in return flows from wastewater (Vicente-Serrano *et al*., 2019, 2021). Likewise, an increase in flood magnitude might result from heavier rainfall, but it could also be amplified – or reduced – by internal catchment changes caused by, for example, urban growth, wetland loss, soil compaction, channel modification or changes in reservoir operating rules (Harrigan *et al*., 2014). For practical management purposes, these distinctions matter. If the cause of change is misdiagnosed, costly interventions could be ineffective or even counterproductive.

The HydroDARE project has built on state-of-the-art attribution science to develop simple methods for better attribution that can be applied in practice, and it has demonstrated the use of these methods across Irish catchments with contrasting hydroclimatic settings, environmental pressures and levels of data availability. Although the HydroDARE project has built on established methods, its novelty is in how it has operationalised these approaches in a modular framework for Irish hydrological series, combining causal-chain attribution, separation of external and internal drivers, data quality assessment and scaling based on projected future warming. This allowed the project to move beyond developing a framework for retrospective detection and attribution towards developing a framework with decision-relevant applications, including in adaptation stress-testing and event-based counterfactual analysis. Through the use of causal chains, the methods developed are grounded in physical understanding rather than just statistical analysis (Hawkins *et al*., 2024), meaning that the framework can provide a clear, step-by-step description of how change in one part of a system can lead to change in another. Causal chains are used to help tell a robust cause-and-effect story from drivers to impacts. For floods, that story might start with changes in global temperature or enhanced moisture supply and then be followed by increased rainfall intensity, covering how primed a catchment already is for floods (antecedent conditions), and end with changes in the magnitude of flood peaks. Unpacking these causal chains helps show where evidence is strong, where it is weaker and where other explanations might be needed.

A further challenge related to attributing causes of change is that monitoring practices and data quality can also change over time (Wilby *et al*., 2017). Over decades, rating curves are updated, gauging structures are modified, channels at measurement sites evolve, instruments are upgraded, processing methods change and stations can be relocated. Similar issues can affect the collection and processing of rainfall and other catchment input data (e.g. Murphy *et al*., 2020). These changes can create apparent trends that look like real hydrological shifts. Considering the observing system as part of any approach to attribution is therefore essential. Before a change can be attributed to external climate or internal catchment changes, being confident that any changes detected are not artefacts of how the data were measured or processed is essential.

Many studies have highlighted the importance of avoiding confirmation bias, or the tendency to favour evidence that supports an expected explanation, in methods used for attribution (Merz *et al*., 2012; Harrigan *et al*., 2014; Slater *et al*., 2021). The methods

developed as part of the HydroDARE project were designed to reduce this risk by treating attribution as a structured evaluation of multiple drivers rather than a search for one preferred answer. The framework developed uses a flexible, step-by-step workflow that can be applied in different contexts depending on the question being asked and the data available. The case studies presented in this report aim to reflect these different contexts. Sometimes, the focus is on inputs to the catchment (e.g. changing rainfall extremes), whereby attribution can be based directly on rainfall indices without needing to reconstruct river flows. In other cases, the focus is on the river response (e.g. changing flood peaks or low flows), and, in these cases, simple statistical approaches are used to separate external (i.e. climate) and internal (e.g. land use) changes. Internal drivers of change can then be assessed independently where possible. Attribution confidence depends on data quality, the robustness of the causal chain and the assumptions used to scale observed relationships based on projected future warming. Key uncertainties include those related to limitations in long-term hydrometric and meteorological records; incomplete representation of catchment processes; the transferability of rainfall–flow relationships beyond the observed period; and the use of global mean surface temperature (GMST) as a simplifying indicator of anthropogenic climate change. For this reason, outputs from the HydroDARE framework are best understood as structured, evidence-weighted assessments of the most plausible drivers of change, with uncertainty and alternative explanations being retained explicitly throughout the analysis.

A key advantage of the HydroDARE approach over traditional detection and attribution approaches is the inclusion of an additional step for cases where observed change can be attributed to climate change; this step enables the scaling of that observed change based on various projected future warming levels, which provides opportunities for event-based counterfactual analysis (Woo, 2019). This unique aspect means that HydroDARE methods enable a move from detecting and attributing past change to providing estimates of how continued change may unfold. If a change detected can be credibly linked to anthropogenic climate change, the relationships become more than an explanation of the past and can be leveraged for planning ahead. In this way, projected changes in climate variables can be used to estimate how flood or drought events are likely to change under different global warming scenarios, thus helping to enable adaptation decision-making that is explicitly tied to the drivers of risk and expanding the toolkit available for developing more effective and practically focused climate services.

The report is structured as follows. In the remainder of this chapter, we outline the key policy objectives of the HydroDARE project and their links to policy, before providing an overview of the framework developed for detection, attribution and scaling. In subsequent chapters, we present focused case studies. Each case study chapter starts with a box comprising a summary of the problem being addressed and a synthesis of the key findings. The final chapter draws together insights from the case studies and presents key recommendations for policy and practice.

## 1.1 Objectives and Policy Relevance

The HydroDARE project's objectives were designed to turn advances in attribution science into practical tools and usable evidence for catchment management by developing a framework that works despite real-world data constraints and provides outputs that can inform both today's decision-making and longer-term climate adaptation. The project also sought to develop a structured and formalised approach to addressing these challenges that can be integrated into practice. The core objectives of the project were threefold:

1. **To develop an operational attribution framework that can be applied to explain changes detected in hydrologically relevant variables.** The methods were designed to separate external climate influences from internal catchment changes, account for data quality variability and provide clear, decision-relevant statements that account for uncertainty.
2. **To develop representative, policy-relevant Irish case studies that span contrasting hydroclimatic settings, environmental pressures and levels of data availability.** These case studies cover key Irish environmental pressures, including floods, drought/low flows, seasonal rainfall extremes and arterial drainage, and produce coherent attribution

narratives that link evidence on drivers to management implications.

3. **To scale observed change based on projected future climate scenarios.** The HydroDARE framework was designed such that, where evidence supports a credible link between an observed change and human-driven climate change, it can be used to scale that observed change based on projected levels of future warming, with the aim of anticipating shifts in key hydrological extremes. In this way, the project aimed to support adaptation planning, by developing a tool that can provide a consistent line of reasoning from detection to attribution and then to plausible future trajectories using empirical data. HydroDARE outputs are directly relevant to a range of EU and Irish policy priorities that depend on understanding and managing non-stationary hydrological risk. At the EU level, the methods developed and the evidence generated will support implementation of the Water Framework Directive, the Floods Directive and the wider EU climate adaptation framework, by strengthening the evidence base for adaptation decision-making in water-related sectors. Nationally, HydroDARE outputs will inform Ireland's climate change adaptation policy, including sectoral and local authority adaptation plans. The framework developed offers the potential to enhance national climate services by providing defensible ways to link observed hydrometric change to climate change and other drivers, quantify uncertainty and, where justified, translate those relationships into implications for future risk. The project findings and outputs will also support communication with the public and help build public trust by producing clear, accessible attribution narratives that explain why river flows and extreme events are changing and what can credibly be linked to climate change versus local pressures.

## 1.2 A Framework for Detection, Attribution and Scaling Based on Future Climate Change Scenarios

The HydroDARE project developed and adopted a structured attribution framework (Figure 1.1) that is intentionally modular; not every application requires every step, and which pathway is appropriate to use depends on the management question being asked. Here, "management question" refers to the decision context motivating the analysis, for example whether the concern is changing rainfall hazards, changing river flow behaviour, the relative influence of climate and catchment changes, or the implications of attributing changes to climate change for future adaptation planning. The stepwise framework developed can be applied in two distinct ways depending on the variable of interest. For meteorological variables (Pathway A), such as rainfall or temperature, the framework proceeds from quality assurance to detection and then to attribution (including, where possible, links to anthropogenic climate change). In this case, flow reconstruction and partitioning of internal versus external changes are not required, because the analysis is carried out on external drivers. For river flow variables (e.g. flood flows, low flows) (Pathway B), additional steps are required to separate climate-driven changes from those caused by catchment modification. In this case, reconstruction/simulation and residual analysis are used to partition external climate forcing from internal change. The following section provides a brief description of the first two key steps of the framework, which are common to both pathways.

### *1.2.1 Commencing the journey*

**Step 1: assemble quality-assured long-term data.** For all applications of the framework, the first step involves assembling quality-assured data and metadata for the variable(s) of interest (e.g. rainfall, temperature, potential evapotranspiration (PET), river flows). In this context, "long-term data" means data collected continuously over a sufficiently long time frame and such data are required to distinguish sustained change from natural interannual to decadal variability. No fixed minimum time frame applies for all variables or catchments, but multi-decadal records are generally required, with longer records, ideally covering 50 years or more, providing greater confidence for attribution, emergence testing and GMST-based scaling. However, even if datasets have been quality controlled or homogenised, the possibility that an apparent change is partly, or in some cases largely, driven by monitoring and processing artefacts should always remain a consideration.

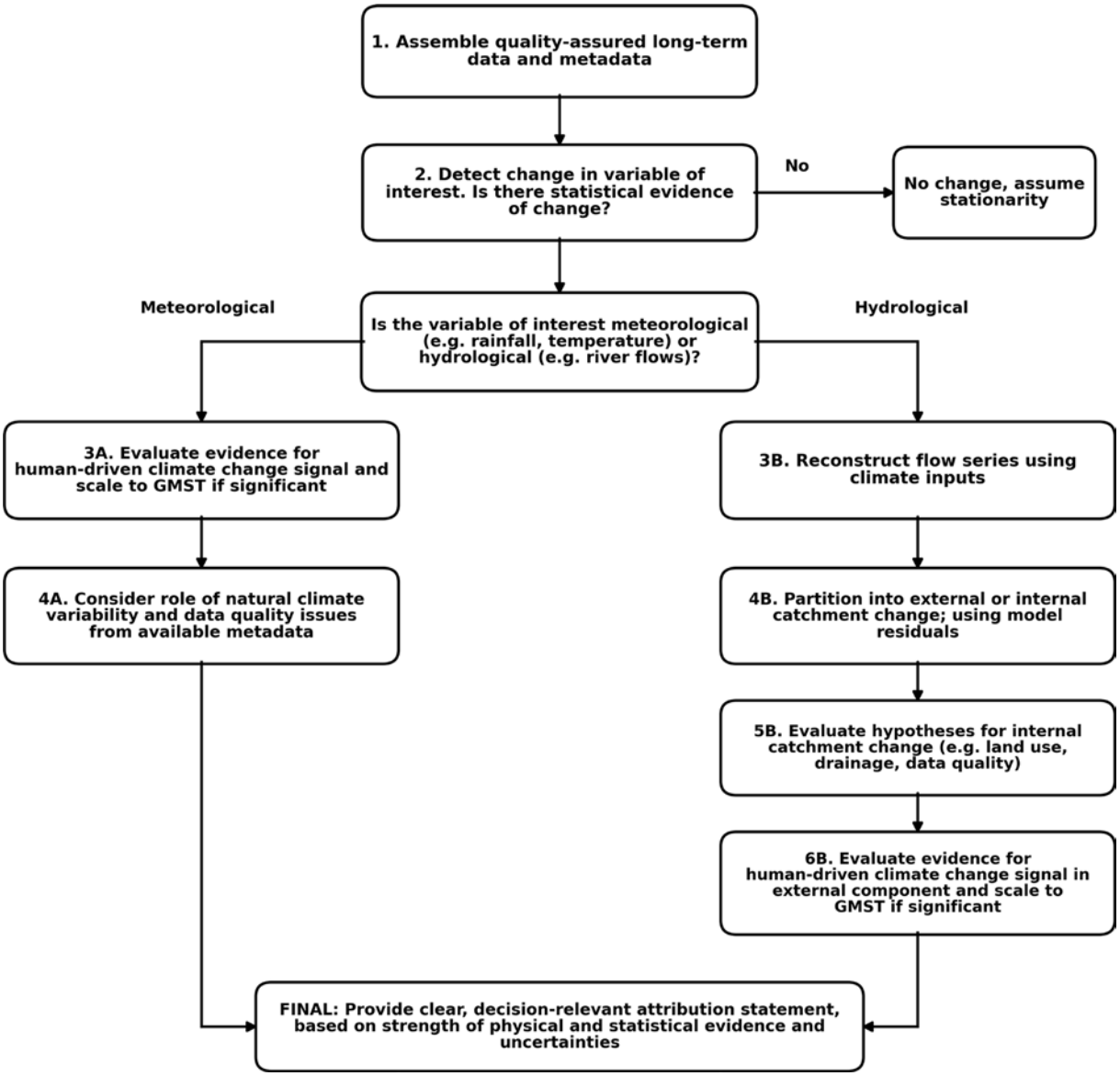



**Figure 1.1. The framework for detection, attribution and scaling based on projected future warming developed by the HydroDARE project. The framework follows one of two pathways: Pathway A for meteorological variables or Pathway B for hydrological variables.**

**Step 2: detect change in the observed variable(s).** The next step is to assess evidence for change in the observed series relevant to the decision problem. This may be an input metric (seasonal precipitation totals, rainfall intensity, multi-day accumulation of rainfall, etc.) or a hydrological response metric (annual maximum flood, seasonal low flows, etc.). Detection is undertaken using standard non-parametric statistical tests for monotonic and step changes. Following an evaluation of the evidence, if no change is detected, a stationarity assumption may be a defensible conclusion for that metric and the time period analysed. Note that no change being detected does not mean that no change has occurred; it just means that a change cannot be discerned with the required level of confidence using the data available.

### *1.2.2 Pathway A: meteorological applications*

**Step 3A: attribute a cause to changes in meteorological drivers and, if a link to anthropogenic climate change is established, scale based on projected future change.** Where change is detected in meteorological inputs, attribution focuses on understanding whether the changes are consistent with large-scale climate variability and/or

anthropogenic climate change. Where long-term series exist, precipitation and temperature indices can be related to GMST to diagnose the emergence of a climate change signal relative to pre-industrial conditions (or to more recent policy-relevant baseline periods, e.g. 1950–1980) and to quantify the sensitivity of the particular meteorological variable to warming (see Murphy *et al*. (2023a) and Fordham and Murphy (2026)). GMST-based scaling provides a useful empirical bridge between local hydrological change and global warming, but the relationships should not be interpreted as fixed physical laws. They may become non-linear under higher warming levels, shifts in atmospheric circulation or altered catchment conditions, so extrapolations should be reassessed as new evidence emerges. Where a credible link to anthropogenic climate change is established, the fitted relationships can be used to estimate how changes in the selected meteorological variable(s) may evolve under different warming levels or scenarios, providing directly usable information for climate services and planning. For example, calculation of scaling factors for local rainfall intensity change per 1°C of warming (based on GMST) can be used to examine sensitivity to future climate change and assess whether observed and future changes are consistent with physical understanding and future climate projections. For a full scientific explanation, see Murphy *et al*. (2023a) and/or Fordham and Murphy (2026).

**Step 4A: consider the role of natural variability and data quality.** A key aspect to consider is how natural variability is related to the climate change signal, how climate change is interacting with this variability and whether any insights on data quality might be considered in establishing confidence in conclusions.

### *1.2.3 Pathway B: hydrological applications (river flows)*

**Step 3B: reconstruct the hydrological response expected from climate inputs (conditional).** Where change is detected in river flow variables, the HydroDARE framework reconstructs the target hydrological series (or indicator) using physically motivated predictors to identify causal chains (e.g. event rainfall, multi-day totals, antecedent wetness proxies, seasonal accumulations) and/or parsimonious hydrological models driven by inputs of rainfall and PET.

**Step 4B: partition external and internal changes using residual diagnostics.** The reconstructions in the previous step feed into a central element of the framework, that is, partitioning observed change into (1) external climate-driven change, assessed through the reconstructions, and (2) internal change, diagnosed through structure in reconstruction residuals (trends, step changes, etc.) and departures from causal-chain expectations. Internal change is interpreted broadly to include both catchment change (land use change, drainage, urbanisation, engineering works, abstractions/returns) and observation system change (inhomogeneities in measurement and processing).

**Step 5B: evaluate internal change hypotheses with independent evidence.** Where residuals indicate trends over time, the framework uses metadata and independent datasets to test multiple working hypotheses about internal drivers. It gives attention to plausibility, timing, directionality and, where possible, quantification, recognising that drivers can interact (Harrigan *et al*., 2014). Regressing available data on arterial drainage, land use, etc., onto residuals can be useful.

**Step 6B: link the external component to anthropogenic climate change and scale based on projected future change (conditional).** Using causal chains, the HydroDARE framework links relevant climate inputs to anthropogenic warming (e.g. via GMST-based scaling using the same approach as that taken in steps 3A and 4A in Pathway A) and propagates that information through a causal chain (using the same models as those used in Step 3B) to assess implications for floods, droughts or other flow metrics, keeping uncertainties explicit. This approach uses the methods described by Hawkins *et al*. (2020) and implemented for Irish data by Murphy *et al*. (2023a) and Fordham and Murphy (2026).

### *1.2.4 Final step: synthesis and extended application*

The endpoint of the framework is an evidence synthesis that integrates detection robustness, data quality considerations and attribution results, and links to anthropogenic climate change. Conclusions are presented transparently, with uncertainty and alternative explanations stated explicitly if necessary, providing a route to more rigorous attribution. The

framework can also be extended to counterfactual analysis, to answer “what if” questions, such as how extremes might change with continued warming. This can be done using the relationships identified with GMST-based scaling for components of the causal chain showing a significant climate change signal. This allows the framework to move beyond retrospective analysis to evaluating sensitivity to future changes, stress-testing adaptation actions or developing storylines for planning and communication.

## 1.3 Conclusion

Attribution of the causes of observed changes is critical for cost-effective catchment management and adaptation. The HydroDARE project developed and applied a framework for rigorous attribution that can extend to scaling impacts, where a climate change signal is evident, based on projected future change, thus informing current and future decision-making. Before detailing the application of the framework in specific case studies, it is crucial to note that our ability to detect and attribute hydrological change ultimately depends on the long-term commitment of organisations such as Met Éireann, the Office of Public Works (OPW), the EPA, local authorities and other monitoring bodies to maintaining and archiving hydrometric and meteorological observation data and carrying out quality control on those data. Allied to the ongoing collection of observation data, robust detection and attribution depends on data rescue through the recovery, digitisation and curation of historical records (including paper archives) that extend time series back in time and provide the long-term records needed for rigorous analysis (e.g. Noone *et al*., 2016; Ryan *et al*., 2018, 2021, 2022; Mateus *et al*., 2020; de Smeth *et al*., 2024). Many of the advances in detection and attribution achieved in this project were possible only because rescued data could be used to lengthen the records available, improve spatial coverage and enable more robust testing of trends, step changes and causal links. Continued investment in both monitoring and data rescue will therefore be a foundational enabler of effective catchment management and climate adaptation planning in the future, and this should be supported as fully as possible. Overall, the HydroDARE project has demonstrated that combining sustained observations with a transparent, process-consistent attribution framework strengthens confidence in explaining past change and, where justified, in translating that evidence into decision-relevant insights on future hydrological risk.

# 2 A Climate Change Signal in Seasonal Rainfall Extremes

## 2.1 Case Study Overview

**Box 2.1. Seasonal rainfall extremes: case study overview**

**Hazard:** increasing intensity of seasonal rainfall extremes.
**Region (seasonal hazard window):** western Ireland (winter–spring) and south-east Ireland (summer–autumn).
**Relevant sectors:** flood risk management, infrastructure, land use planning, agriculture, water services.
**Period analysed:** 1930–2019 (observations); emergence of climate change signal assessed relative to 1850–1900 and 1950–1980 baselines.
**HydroDARE framework:** Pathway A (meteorological).
**Primary policy relevance:** provides evidence that a climate change signal in rainfall extremes has already emerged beyond historical variability in parts of Ireland.
**Key finding:** a climate change signal in rainfall extremes has already emerged beyond historical variability in parts of Ireland.

## 2.2 The Problem and the Policy Context

As the climate warms, the atmosphere can hold more moisture, increasing the likelihood of intense rainfall (Pall *et al*., 2007; Murphy *et al*., 2023b). This can translate into heavier rainfall over short periods and multi-day events, with direct implications for flooding, drainage systems, agriculture, soils and water quality (Mellander *et al*., 2024). Heavy rainfall can trigger floods when catchments are already wet, overwhelm urban drainage, and mobilise sediments and nutrients, which then enter rivers and lakes. This matters for policy because many current design standards and planning assumptions are still rooted in past rainfall conditions (Milly *et al*., 2008). If rainfall extremes have already shifted beyond historical variability, then some flood risk, infrastructure and land management decision-making may be based on underestimations of current and future risks.

## 2.3 Detection and Attribution Approach

This case study applied HydroDARE Pathway A, which was designed for meteorological variables (e.g. rainfall). Full details of the scientific analysis performed are published in Fordham and Murphy (2026), with the key steps and findings being outlined here. In line with the framework set out in Chapter 1, the approach followed a clear sequence: (1) assemble quality-assured long-term observational records; (2) test whether change can be detected; (3) evaluate whether the change detected is consistent with anthropogenic climate change; and, where evidence is sufficient, (4) estimate how the observed change would differ under conditions of additional warming using GMST-based scaling.

**Data and study area:** the analysis used long-term quality-assured daily rainfall observation data from 36 stations across Ireland (1930–2019) (Ryan *et al*., 2020) and focused on two policy-relevant rainfall indices:

- The maximum consecutive 5-day precipitation (RX5day) total for winter (December, January, February): the highest 5-day consecutive rainfall total in winter can be used as an indicator of multi-day rainfall events that can trigger flooding when catchments are already saturated.
- The Simple Daily Intensity Index (SDII) for summer (June, July, August): based on the average rainfall intensity on wet days, this index can be used to assess whether rainfall is becoming heavier, even where seasonal totals may not increase. This metric is important for estimating short-duration impacts such as drainage exceedance, increased run-off and erosion, and water quality pressures.

**Detection of change:** evidence for trends in each indicator were evaluated using the modified Mann–Kendall test (Yue and Wang, 2004), which accounts for possible autocorrelation in the data. Evidence for trends is evaluated at the 0.05 significance level ($p < 0.05$). Trend magnitude was evaluated using the relative Sen's slope estimate (Yue and Hashino, 2007).

**Attribution, emergence and scaling** of the climate change signal were undertaken by regressing each extreme rainfall variable onto smoothed GMST anomalies as a physically meaningful indicator of anthropogenic warming. This step tested whether changes in Irish rainfall extremes track broader warming in a way that is consistent with climate change expectations (Murphy *et al*., 2020; Fordham and Murphy, 2026). This provided three linked insights:

1. **Evidence of attribution:** this indicates whether the changes observed in both rainfall indices are statistically related ($p < 0.05$) to a warming-related signal rather than to internal variability alone.
2. **Emergence of a climate change signal:** a key part of attribution is testing whether warming-related changes in rainfall extremes have emerged from background climate variability. In practical terms, this asks whether current conditions remain within the range considered historically typical. This is assessed using a signal-to-noise ratio (SNR), where the signal is the estimated climate-related change in the rainfall index and the noise is the historical variability of that index around a baseline climate. The signal is estimated by regressing each rainfall extreme index onto GMST, which quantifies how much the index changes per 1°C of warming. That fitted relationship is then used to calculate the expected climate-related shift relative to a chosen baseline, and this shift is compared with historical variability around that baseline to derive the SNR value. In this case study, emergence was assessed relative to two baselines: 1850–1900 (early industrial) and 1950–1980 (a more policy-relevant modern baseline aligned with many planning assumptions) (Ossó *et al*., 2022). An SNR of $>|1|$ was considered to indicate the emergence of a climate change signal, meaning that the climate-related shift is larger than typical historical variability around the chosen baseline (Hawkins *et al*., 2020).
3. **Scaling local change based on a climate change signal:** where a significant relationship with GMST is found, the regression slope can be used to establish the change in the rainfall index per 1°C of global warming, which provides a clear, interpretable metric of sensitivity that can be used in adaptation planning.

## 2.4 Key Results

### *2.4.1 Winter multi-day rainfall is increasing in western Ireland*

Western Ireland shows the clearest evidence of increasing trends in winter RX5day totals. At several western and north-western stations, these changes are significantly related to GMST, with the climate change signal having already emerged relative to the early industrial baseline (SNR > 1), meaning that current winter multi-day rainfall extremes are now outside the range of early industrial conditions (Figure 2.1). Many stations are also approaching this threshold relative to the 1950–1980 baseline. The rate of change is substantial: winter RX5day totals for the west are estimated to have increased by roughly 12–20% per 1°C of global warming.

### *2.4.2 Summer rainfall is becoming more intense in the south-east*

The strongest summer signal was found in the south-east, where the SDII shows more intense rainfall on wet days (Figure 2.1). Observed patterns indicate fewer wet days but more intense rainfall when rain does occur (see Fordham and Murphy, 2026). Several stations in the south-east now show the emergence of a climate change signal (SNR > 1) in rainfall intensity relative to early industrial levels. Moreover, numerous stations are nearing this threshold relative to the modern baseline (1950–1980). The magnitude of change exceeds the Clausius–Clapeyron rate of approximately 6–7% per 1°C of warming (Pall *et al*., 2007). This indicates a shift towards heavier rainfall events, even though total summer rainfall has not increased. Several stations now show an emerging climate change signal relative to the early industrial baseline (1850–1900), and many are close to showing emergence relative to 1950–1980.

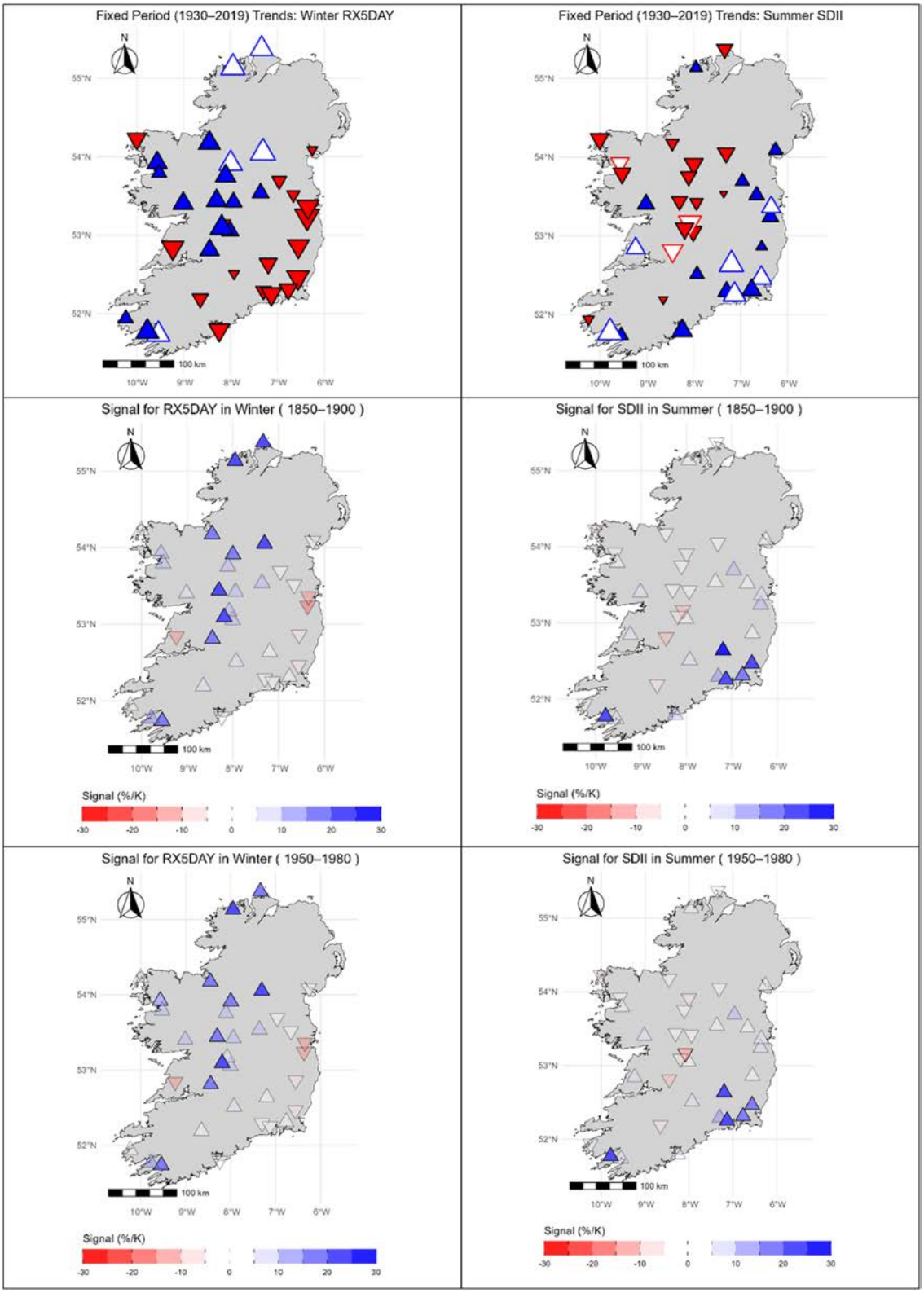



**Figure 2.1. The top panels show trends in winter (left) and summer (right) indices for the period 1930–2019, with the direction of each triangle showing whether a trend is increasing (blue) or decreasing (red) and significant trends being denoted by white-filled triangles. The middle and bottom panels show the scaling of local changes in each indicator based on an increase in GMST (percentage change for a 1°C rise in GMST) relative to the early industrial period (1850–1900) (middle panels) and a more modern baseline (1950–1980) (bottom panels). The directions indicated by the triangles representing different stations show the direction of change, with greyed out triangles indicating no significant relationship with GMST (i.e. $p > 0.05$). %/K, percentage change per 1°C of warming in GMST.**

## 2.5 Assumptions and Limitations

This analysis assumed that long-term station records and selected rainfall indices provide a reliable basis for detecting climate-related change, and that observed relationships with GMST can be used for the approximately linear scaling of rainfall extremes based on projected future warming. The attribution of increases in rainfall extremes to increases in GMST captures the main climate change signal, but it does not fully elucidate the role of dynamic circulation variability or local impact pathways, namely vulnerability, exposure and how flood hazards materialise locally. Readers are encouraged to consult Fordham and Murphy (2026) for full scientific details of this case study.

## 2.6 Key Messages and Policy Implications

- Flood-relevant rainfall extremes have already increased in parts of Ireland beyond historical variability, indicating that climate change is now affecting observed flood-generating rainfall.
- In western Ireland, increases in winter multi-day rainfall (RX5day) totals are emerging, with implications for fluvial and groundwater flood risk. These increases put increased pressure on flood defence standards, asset maintenance, drainage capacity and catchment-scale flood management. Comparable changes are also evident in spring multi-day rainfall totals (Fordham and Murphy, 2026).
- Summer rainfall intensity is also increasing, particularly in the south-east, raising the risk of short-duration flooding, including localised surface water flooding and increasing environmental pressures on agriculture, soils and water quality. A similar increase is also evident in autumn rainfall intensity (Fordham and Murphy, 2026).
- Many of the changes observed are apparent relative to the 1950–1980 baseline, as well as the early industrial baseline (1850–1900), suggesting that legacy assumptions embedded in infrastructure design, planning guidance and operational practice may no longer be appropriate for current conditions.
- Incorporating the changes observed in multi-day rainfall totals and summer rainfall intensity into planning and adaptation decision-making is essential for ensuring that responses remain proportionate to current and emerging risks.

# 3 A Climate Change Signal in Shannon Peak River Flows

## 3.1 Case Study Overview

**Box 3.1. Shannon floods: case study overview**

**Hazard:** river flooding (annual maximum flows, measured using instantaneous annual maximum (IAMAX) data).
**Region:** Shannon catchment, western Ireland (hydrometric areas 25 and 26).
**Relevant sectors:** flood risk management, water infrastructure, catchment management, climate adaptation.
**Periods analysed:** 1980–2020 (flood peak flows); 1910–2022 (long-term rainfall indicators).
**HydroDARE framework:** Pathway B (hydrological).
**Primary policy relevance:** provides an observation-based way of tracking climate-driven flood risk, quantifying flood sensitivity to warming and informing adaptation pathway triggers/tipping points.
**Key finding:** increases in flood magnitude observed in the Shannon catchment are predominantly climate driven, mainly through changes in heavy and multi-day rainfall, with increases in peak flows (IAMAX levels) already being seen to range from approximately 7.5% to 18.1% per 1°C increase in GMST (depending on the catchment). It is likely that historical implementation of arterial drainage works has amplified the sensitivity of floods to climate change.

## 3.2 The Problem and the Policy Context

Floods are among the most damaging natural hazards, and their frequency and magnitude are expected to increase under a warming climate (Murphy *et al*., 2023c). While individual flood events can often be attributed to human influence (e.g. Clarke *et al*., 2024; Bergin *et al*., 2025), detecting a long-term climate signal in flood records remains difficult because of natural variability, land use change, drainage works and data limitations (Scussolini *et al*., 2024). This case study developed and applied a framework for detecting, attributing and scaling flood risk through causal chains that link global temperature rise to local hydrological impacts. Causal chains describe physically consistent pathways connecting large-scale climate drivers such as increasing GMST to local flood responses (Hawkins *et al*., 2024). By tracing links from temperature to precipitation to flood magnitude, the framework was used to quantify how much of the change observed arises from climate forcing and how much arises from internal catchment processes. Applied to the Shannon catchment in Ireland, it disentangled climate and non-climate influences, providing evidence for the emergence of an anthropogenic signal in flood-relevant precipitation that explains the observed increases in flood magnitude. The framework, although used for floods in this case study, is readily extendable to droughts and low-flow extremes, offering a scalable, observation-based tool for assessing climate impacts on water systems.

## 3.3 Detection and Attribution Approach

This case study applied HydroDARE Pathway B, designed for hydrological variables, following the approach set out in the Chapter 1. The workflow comprised six steps: (1) assemble quality-assured discharge and precipitation data; (2) detect changes in observed flood series; (3) reconstruct flood behaviour from flood-relevant precipitation indices (causal chains); (4) partition climate-driven and internal/non-climatic components using model residuals; (5) test whether causal-chain precipitation indices show a warming-related signal using GMST; and (6) propagate uncertainty to scale local flood sensitivity based on projected future warming. The analysis combined standard non-parametric trend tests, regression-based causal chains and Monte Carlo uncertainty

propagation, making the workflow transparent and repeatable across catchments where long-term rainfall series exist.

**Data and study area:** IAMAX flood series were derived from 15-minute flow data for 24 OPW gauges in the Shannon catchment (1980–2020, by hydrological year, i.e. from October to September, with each year being based on the year in which October falls) (Figure 3.1). Sub-catchments in the Shannon catchment span a wide range of sizes and hydrogeological settings. Met Éireann's daily 1-km-gridded precipitation data were used to compute candidate indices such as annual maximum 30-day totals; annual, seasonal and monthly multi-day rainfall maxima (spanning 2–30 days); and counts of heavy-rainfall days. A full list of the indices considered is provided in Table 3.1. These indices represent antecedent catchment wetness and flood-generating rainfall events. Six long-term station series (1910 onward), developed and quality-assured by Ryan *et al*. (2020), were also used to extend key indices for emergence analysis against GMST.

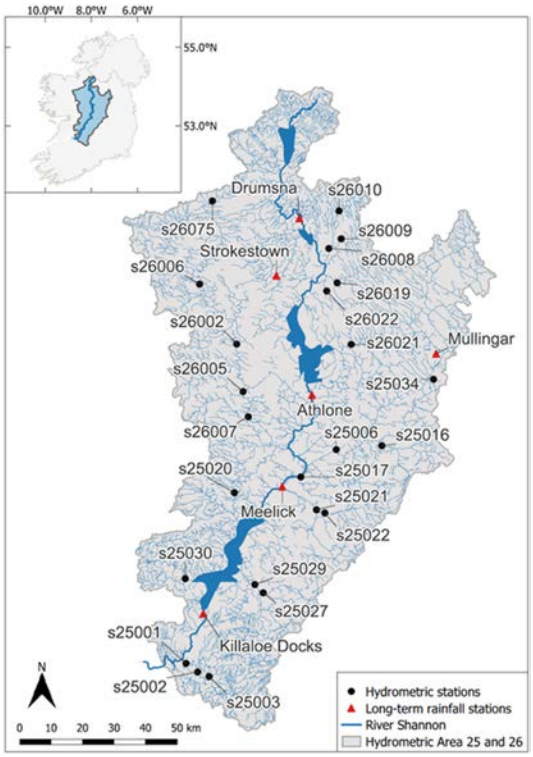



**Figure 3.1. The location of each of the 24 OPW discharge gauges used for assessing changes in IAMAX values in the Shannon catchment (hydrometric areas 25 and 26), with the locations of the long-term precipitation series stations used in the analysis also being shown.**

**Detection of change:** trends in IAMAX data were assessed using the modified Mann–Kendall test (to account for autocorrelation), with Sen's slope being used to estimate magnitude and the Pettitt test being used to detect step changes. Evidence was assessed for statistical significance ($p < 0.05$).

**Reconstruction and partitioning:** moving from detection to attribution, series with significant IAMAX trends were reconstructed. These models represent the causal chain from precipitation to flood magnitude, with the modelled IAMAX series being interpreted as the climate-driven component operating through precipitation forcing. Model residuals were used to help identify potential internal or non-climatic influences, such as land use change, drainage, hydrometric issues or data quality problems. It should be noted that some residual structure may also reflect limitations in the precipitation–flood model itself, including unrepresented processes or incomplete predictor choice, meaning that inference should be interpreted alongside independent supporting evidence such as drainage history, gauge metadata and local catchment information. Model selection was based on an exhaustive search with cross-validation, along with checks for significance, multicollinearity, residual independence and residual normality.

**Partitioning and consistency checks:** the contribution of changes in precipitation to observed IAMAX trends was quantified by simulating fitted values and comparing Sen's slopes of modelled versus observed series. Trend consistency was then checked across the selected precipitation indices to confirm the physical pathway (e.g. whether increases in IAMAX values aligned with increases in multi-day heavy-rainfall totals rather than with broad changes in wet-day frequency). This is a key safeguard in the framework based on causal chains. The reliability of attribution evidence is strengthened when the hydrological change detected and the intermediary meteorological changes tell the same story.

**Attribution and emergence:** long-term, flood-relevant precipitation indices identified by the regression models were regressed onto hydrological-year GMST anomalies (relative to 1850–1900) to test for a

**Table 3.1. Precipitation indices derived for identifying possible predictors of IAMAX flood levels in each catchment**

| Index name | Abbreviation | Unit | Definition | Annual | Seasonal | Monthly |
|---|---|---|---|---|---|---|
| Total wet day precipitation | PRCPTOT | mm | Total precipitation days ≥ 1 mm | ✓ | ✓ | ✓ |
| Consecutive dry days | CDD | days | Maximum number of dry days when precipitation < 1 mm | ✓ | | |
| Consecutive wet days | CWD | days | Maximum number of wet days when precipitation < 1 mm | ✓ | | |
| Number of heavy precipitation days | R10mm | days | Number of precipitation days ≥ 10 mm | ✓ | ✓ | ✓ |
| Number of very heavy precipitation days | R20mm | days | Number of precipitation days ≥ 20 mm | ✓ | ✓ | ✓ |
| Maximum consecutive 1-day precipitation | RX1day | mm | Maximum 1-day precipitation total | ✓ | ✓ | ✓ |
| Maximum consecutive 5-day precipitation | RX5day | mm | Maximum 5-day precipitation total | ✓ | ✓ | ✓ |
| Maximum consecutive 30-day precipitation | RX30day | mm | Maximum 30-day precipitation total | ✓ | | |
| Maximum consecutive 50-day precipitation | RX50day | mm | Maximum 50-day precipitation total | ✓ | | |
| Very wet days | R95PTOT | mm | Precipitation total on days exceeding the 95th percentile of daily precipitation in the baseline period 1961–1990 | ✓ | | |
| Extremely wet days | R99PTOT | mm | Precipitation total on days exceeding the 99th percentile of daily precipitation in the baseline period 1961–1990 | ✓ | | |
| Simple Daily Intensity Index | SDII | mm/day | Ratio of total precipitation to number of wet days (≥ 1 mm) | ✓ | ✓ | ✓ |

**The selected predictors become the causal chains linking precipitation and floods, and they represent the timing, antecedent conditions and flood-triggering events.**

warming-related signal and estimate SNRs. An SNR of > 1 was used to indicate emergence.

**Scaling flood sensitivity based on projected future warming:** flood sensitivity to climate change was estimated using the established causal chains, whereby global warming (indicated by increasing GMST) affects flood-generating rainfall and changes in that rainfall affect annual maximum flows (measured using IAMAX data). For each catchment, data on the sensitivity of key rainfall indicators to GMST were combined with data on the strength of the rainfall–flood relationship, then the result was expressed as a percentage change in IAMAX per 1°C of warming. Only rainfall indicators that show a statistically significant relationship with GMST were included. Uncertainty was propagated using Monte Carlo simulation (10,000 runs), and results were scaled based on projected future warming levels of 1.5–4°C above the early industrial baseline to provide adaptation-relevant flood change scenarios.

## 3.4 Key Results

### *3.4.1 Flood magnitude is increasing at most Shannon gauges*

Of the 24 IAMAX series analysed, 22 show increasing trends and 10 show statistically significant increases ($p < 0.05$). The largest increases (based on a modified Mann–Kendall test, $Z > 3$) occur at gauges s26075, s25020, s25017 and s26007. The pattern is not purely monotonic: three stations show significant step changes only (e.g. breaks around 1983, 1985 and 1991), while five show both step changes and ongoing monotonic trends. This mixed behaviour is important because it signals different drivers of change.

### 3.4.2 Causal-chain reconstruction identifies the dominant flood drivers

Linear regression-based reconstructions for the 10 gauge series showing significant change also show strong reconstruction skill (mean $R^2$ of about 0.71, range 0.52–0.85), indicating that a substantial share of interannual flood variability can be explained by heavy-precipitation indices (Figure 3.2). These models also offer clearer insights into the benefits of using causal chains over more complex approaches. Standardised coefficients consistently identified multi-day rainfall accumulation and heavy-rainfall frequency as the dominant predictors. Recurrent causal-chain variables include annual maximum 30-day precipitation totals, November and winter 5-day precipitation maxima, and the number of winter days with precipitation exceeding 20 mm. This provides a physically coherent causal chain that includes antecedent conditions, flood-generating events and the timing of floods at the catchment scale.

### 3.4.3 Precipitation change explains most of the observed increase in flood magnitude

Monte Carlo analysis indicates that precipitation change explains most of the observed IAMAX trends in many catchments, but not all. For example, the estimated precipitation contribution is very high at s25017 (median of about 93%, with an uncertainty range of about 77–100%), while it is much lower at s26009 (about 28%, range 14–43%). Several other gauges fall in the broad 60–80% range (e.g. s25016, s25020, s25021, s25029, s26075 and s26008). Climate-linked precipitation change is the dominant explanation for increased flood magnitude across much of the Shannon network, but residual trends at some gauges suggest that internal factors may amplify or obscure the climate change signal, including arterial drainage and hydrometric complications (e.g. possible backwatering effects at gauge s25020, which are seen as an increase in residuals post 2010 in Figure 3.2).

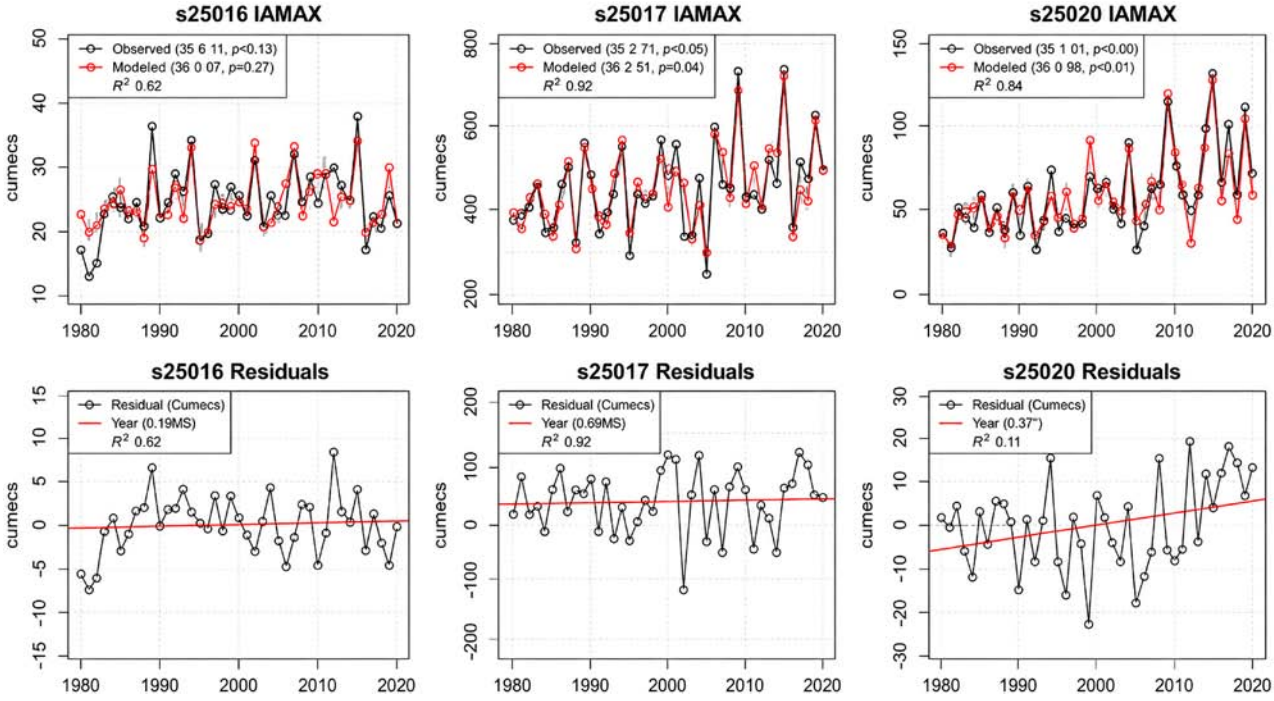



**Figure 3.2. Observed (black line) and reconstructed (red line) IAMAX series, along with residual time series for example catchments s25016, s25017 and s25020. The legends on each panel show observed and reconstructed trend magnitudes (Sen's slope), the *p*-value for trends assessed using the Mann–Kendall test and the $R^2$ value representing the percentage variance captured by the respective models. For the residual plots, the coefficient derived from regressing year onto the residual series in each catchment is given, along with an indication of its significance (*$p < 0.05$). Cumecs, cubic metres per second; NS, not significant.**

### 3.4.4 *Heavier rainfall on wet days explains antecedent conditions and flood-generating events*

The intermediary precipitation indices selected by the flood models also show coherent trends (Figure 3.3). Significant increases were found in annual maximum consecutive 30-day precipitation (RX30day) totals and winter heavy-rainfall day counts (> 20 mm), mirroring the increase in IAMAX values. The evidence suggests that the rise in RX30day totals is driven by an increase in the number of heavy-rainfall events within those windows rather than by a broad increase in the number of wet days. There is also no clear shift in the timing of the annual RX30day totals, which is physically consistent with a thermodynamic intensification signal (a warmer atmosphere holding more moisture) without a necessary shift in flood seasonality.

### 3.4.5 *Flood-generating rainfall indices show a clear climate change signal*

When extended using the long-term Shannon station series and regressed onto hydrological-year GMST anomalies, several flood-relevant precipitation indices show statistically significant relationships with warming ($p < 0.05$). The clearest examples are RX30day totals, winter heavy-rainfall day counts (win.r20 mm) and spring heavy-rainfall day counts (spr.r20 mm). SNRs exceed the emergence threshold (i.e. SNR > 1) relative

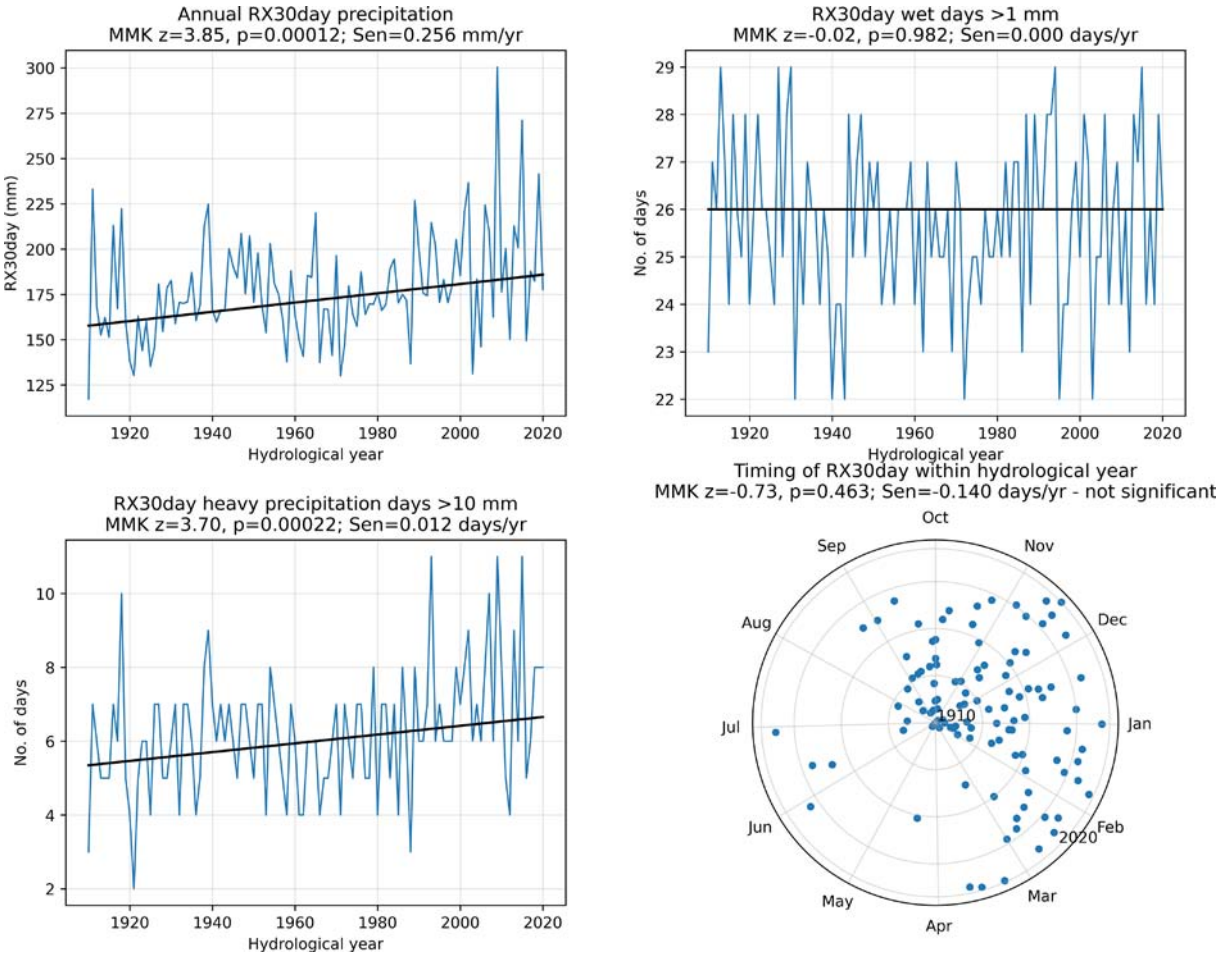



**Figure 3.3. Assessment of trends in RX30day totals for the long-term (1910–2022) Shannon average series (mean of six long-term station records), including the annual RX30day series (top left), the number of wet days (> 1 mm) in each annual 30-day window (top right), the amount of heavy-precipitation data (> 10 mm) in each 30-day window (bottom left) and the timing of occurrence (Julian Day per hydrological year) of the RX30day totals in each year (bottom right). Also provided for each series are the trend magnitude (Mann–Kendall score) and the associated *p*-value for the derived trend.**

to the early industrial period, with reported SNR values of about 1.26 for RX30day and 1.08 for both win.r20 mm and spr.r20 mm. This demonstrates that the IAMAX causal chain for the Shannon catchment contains a detectable anthropogenic climate change signal.

### *3.4.6 Flood sensitivity to climate change varies markedly across catchments*

Propagating uncertainty in both GMST-to-precipitation and precipitation-to-IAMAX links yields catchment-specific sensitivity estimates in percentage change in IAMAX per 1°C increase in GMST. Median sensitivities span a substantial range, from about 7.5% per 1°C increase at s25021 to about 30% per 1°C increase at s25020. This wide range implies that warming does not translate into a uniform flood response across the Shannon catchment and that the local hydrogeomorphic context modulates sensitivity (Figure 3.4). Preliminary evidence suggests that catchments with extensive historical arterial drainage show the strongest flood sensitivity to warming, implying an amplifying interaction between internal catchment change and climate forcing. Extrapolated to policy-relevant warming thresholds (relative to early industrial), the analysis returns indicative average IAMAX increases in the Shannon catchment of roughly 29% at 2°C warming. The most sensitive catchment is s25020, with a median increase of 34% at 2°C warming. By 3°C global warming, mean increases in IAMAX range from 14% at s25021 to 64% at s25050 and 51% at 26022.

## 3.5 Assumptions and Limitations

This case study analysis assumed that the regression-based causal chain from rainfall to flood magnitude captures the dominant predictors of IAMAX levels, and that the rainfall–GMST relationships identified can be used to scale flood sensitivity approximately linearly with warming. A key consideration for implementing the framework for this type of study is that the analysis is contingent on the availability of long-term rainfall records. Causal chains are first identified using catchment-based data and then transferred to available long-term rainfall series to assess emergence and perform climate scaling. While detailed metadata are highly valuable for explaining hydrometric contributions to residuals and testing internal change hypotheses, such detailed evidence is not always available for other internal drivers such as land use change, so residual structure may still reflect a combination of drainage, measurement and other catchment influences.

## 3.6 Key Messages and Policy Implications

- Increases in IAMAX flood levels in the Shannon catchment are predominantly climate driven. Heavy and multi-day rainfall are the main pathways through which warming influences flooding. In particular, indicators such as annual RX30day totals and win.r20 mm carry the strongest climate-linked signal and are closely connected to changes in peak flows. These

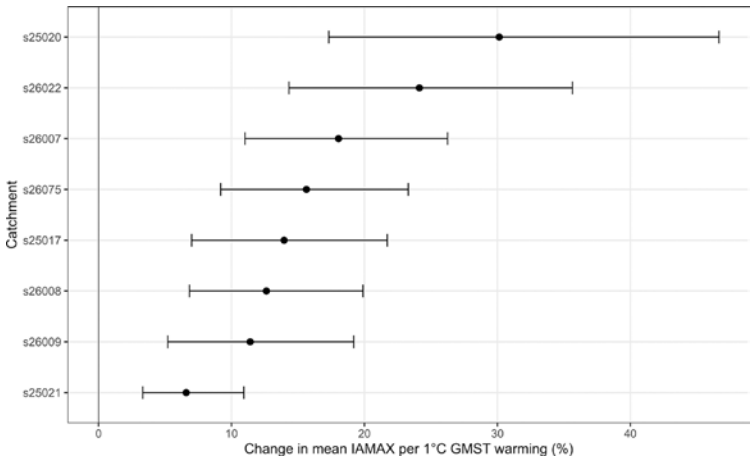



**Figure 3.4. Sensitivity of IAMAX levels in each catchment to an increase of 1°C in GMST derived from causal chains. Plots show median and 95% confidence intervals of changes in IAMAX levels derived by sampling both GMST-to-precipitation and precipitation-to-IAMAX links.**

changes are physically consistent with expected rainfall change in a warming climate.

- By explicitly linking climate change through flood-generating rainfall to IAMAX levels along a causal chain, the framework shows how global warming translates into local changes in flooding and allows each step in the chain to be tested separately.
- Flood sensitivity to warming is already quantifiable from observed data. Across analysed catchments, median increases in IAMAX flood magnitude range from approximately 7.5% to 30% per 1°C increase in GMST, which provides a practical metric for adaptation planning and design stress-testing.
- Internal catchment influences matter and can amplify climate sensitivity. Residual analysis suggests that drainage history can amplify climate-related trends and sensitivity to future rainfall changes. Arterial drainage has been extensively implemented across Ireland and may heighten exposure and vulnerability to climate change.
- Flood-relevant rainfall indices can be used to monitor evolving flood risk, especially where long-term flood records are limited. Flood-generating rainfall indicators (e.g. counts of heavy-rainfall days and multi-day rainfall totals) are often more widely available. Because these indicators are directly linked to flood generation, they provide a practical evidence base for tracking changing risk over time and can be easily integrated into climate change projections and impact studies.
- The causal-chain framework can support the establishment of adaptation tipping points, with flexible baseline choice. The OPW uses adaptation pathways to stage interventions as climate risk changes over time, but a core challenge is identifying when risk has increased enough relative to a baseline to trigger action. This framework helps address that challenge by estimating how flood risk changes as warming progresses and indicating when measures set out in adaptation plans need to be implemented; it can be applied relative to early industrial conditions or to a more recent, adaptation-relevant baseline (as in the case study presented in Chapter 2), making it a flexible tool for both climate attribution and operational planning purposes.
- The framework provides a single integrated basis for informing evidence-based flood policy. It addresses three linked needs at once: detecting and attributing hydrological change, understanding how precipitation changes drive flooding at the catchment scale and scaling observed responses based on projected future changes in GMST to support the implementation of timely interventions.

# 4 A Climate Change Signal for Droughts

## 4.1 Case Study Overview

**Box 4.1. Droughts: case study overview**

**Hazard:** meteorological drought, focusing on increasing evaporative demand-driven drought severity.
**Region:** County Wexford, south-east Ireland.
**Relevant sectors:** water resources and public water supply, agriculture, ecosystems, drought monitoring, climate adaptation planning.
**Period analysed:** 1900–present.
**HydroDARE framework:** Pathway A (meteorological).
**Primary policy relevance:** informs operational drought planning, monitoring and early warning systems, water resource planning and adaptation to increasing drought severity under warming.
**Key finding:** no attributable climate change signal can be detected using precipitation-only drought metrics, but a clear signal for drought severity has already emerged in increased evaporative demand.

## 4.2 The Problem and the Policy Context

Evidence from recent droughts and a growing body of Irish research show that drought is already a material risk for public water supply, agriculture, freshwater ecosystems and water quality (Wilby *et al*., 2015; O'Connor *et al*., 2022; Meresa and Murphy, 2023; Murphy *et al*., 2023b; Jobbová *et al*., 2024). County Wexford provides a useful location for a case study of this wider Irish challenge. The county is agriculturally important, its public water system has experienced numerous hosepipe bans in recent years and it is exposed to spring–summer moisture deficits, with drought being identified, in the Wexford County Council Climate Action Plan 2024–2029 (Wexford County Council, 2024), as a common hazard under current climate conditions and one that is likely to become more frequent. The county is also frequently mentioned in the Irish Drought Impacts Database, which was derived from newspaper and impact records and compiled by Jobbová *et al*. (2024).

The consideration of two physical factors is central to understanding the causal chain of drought risk in the context of climate change (Vicente-Serrano *et al*., 2022). The first is precipitation deficit, which remains the primary driver of drought onset in Ireland. The second is evaporative demand, that is, the atmosphere's demand for moisture from soils, vegetation and open water. Evaporative demand rises as the atmosphere warms, increasing PET. In effect, warming increases atmospheric moisture demand, accelerates soil moisture loss and amplifies drought severity independent of changes in rainfall totals. It should be noted that local soil type can act as a limiting factor for the amount of moisture that can be lost through evaporation. Soils with greater capacity may have more resilience or be less sensitive to evaporation as a driver of drought. This distinction matters for policy because drought risk assessments based solely on precipitation indices may underestimate warming-driven increases in drought severity, and this is consistent with previous research. Irish studies have identified increasing summer drought severity in observational records and projected higher levels of seasonal drying and more severe drought deficits when temperature-driven evaporative demand is included (e.g. Meresa and Murphy, 2023; O'Connor *et al*., 2024). Similar warming-driven intensification of evaporative demand and therefore drought severity has been documented internationally, reinforcing confidence that this mechanism is physically robust and not region specific (Vicente-Serrano *et al*., 2020). The policy implication is that drought monitoring and planning in Ireland should move beyond considering precipitation metrics alone to tracking the combined influence of rainfall deficits and increasing atmospheric thirst, to ensure that emerging climate risks are not underestimated.

## 4.3 Detection and Attribution Approach

This case study applied HydroDARE Pathway A, designed for meteorological variables. Using widely deployed drought metrics (the Standardised Precipitation Index (SPI) and the Standardised Precipitation–Evapotranspiration Index (SPEI)), the evidence for a climate change signal in annual and seasonal drought series was examined. The impact of increasing temperatures on evaporative demand was also investigated by examining differences in SPEI derived using average monthly PET and SPEI derived using the observed PET series. The resulting data series, henceforth referred to as ΔSPEI, provides insight into the role of enhanced evaporative demand (associated with a warmer atmosphere) in making droughts more severe. Seasons were defined as the standardised drought series at 3-month accumulation for February (winter), May (spring), August (summer) and November (autumn). Annual droughts were characterised using data for December and a 12-month accumulation period. The workflow comprised three steps: (1) assemble quality-assured data and extract drought indices; (2) evaluate evidence for trends; and (3) evaluate evidence for a human-driven climate change signal in series showing trends.

**Data and study area:** local climate records were assembled to construct continuous monthly series for temperature and precipitation for County Wexford. A bespoke monthly precipitation series from 1900 to present was developed by combining (simple average) records from Foulksmills and Johnstown Castle. In parallel, a monthly temperature series from 1900 to present was produced by merging daily observations from Johnstown Castle with earlier estimates infilled using Twentieth Century Reanalysis (20CR) data (Slivinski *et al*., 2019), and data were bias-adjusted to ensure consistency with the observed station records (correlation for overlap with daily observations after bias correction = 0.93) (Figure 4.1).

Once aggregated to monthly means, these temperature data were used to estimate PET and effective rainfall (Precipitation – PET) via a widely used method first described by Oudin *et al*. (2005) and used to fit the SPEI series in calculating ΔSPEI. Together, these extended precipitation and temperature series provided a robust basis for tracking drought variability and change in County Wexford, and for assessing the extent to which precipitation change, rising temperatures and increasing atmospheric evaporative demand may be intensifying drought severity.

**Detection of change:** trends in drought series were assessed using the modified Mann–Kendall test (to account for autocorrelation), with Sen's slope being used to estimate magnitude and the Pettitt test being used to detect step changes. Evidence was assessed for statistical significance ($p < 0.05$).

**Attribution and emergence:** long-term annual and seasonal SPI and ΔSPEI series showing evidence of significant trends were regressed onto smoothed GMST anomalies (relative to 1850–1900) to test for a warming-related signal and estimate SNRs. An SNR of > 1 was used to indicate emergence, indicating that the externally forced signal exceeds background variability. See Fordham and Murphy (2026) for full details of the methods used.

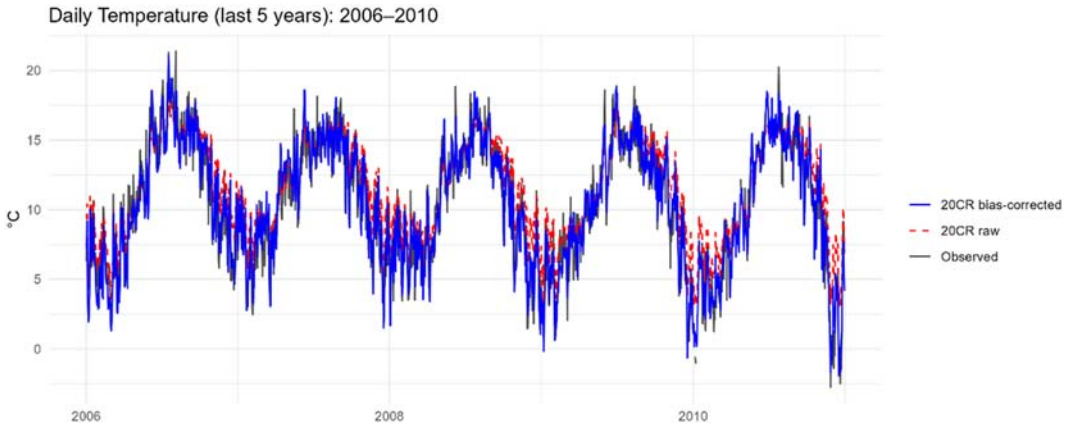



**Figure 4.1. Comparison of observed, raw and bias-corrected 20CR temperature data for the period 2006–2010.**

## 4.4 Key Results

### *4.4.1 No clear evidence of a climate change signal for drought can be found in precipitation indices*

Analysis of the SPI, which is indicative of only precipitation as a driver of droughts, shows a significant negative trend (towards more severe droughts) in summer; however, when regressed onto GMST anomalies, there is no clear evidence of a climate change signal driving these summer trends. It is more likely, therefore, that decreasing summer rainfall trends are associated with natural climate variability. Non-significant negative trends in winter and non-significant increasing trends in other seasons and annually were found, none of which could be attributed to climate change.

### *4.4.2 Increased evaporative demand shows a clear climate change signal and makes droughts more severe when they do occur*

ΔSPEI shows declining trends in all seasons, indicating that increasingly severe drought deficits are associated with rising evaporative demand. These trends are statistically significant ($p < 0.05$) in every season except summer, and are also significant ($p < 0.05$) in the annual series. Regressing the series with significant trends onto GMST anomalies yields significant relationships in all cases. In addition, the SNRs indicate that the climate change signal has emerged from background variability (SNR > 1 in absolute terms) in winter (SNR = –1.30), spring (SNR = –1.01), autumn (SNR = –1.74) and the annual series (SNR = –3.07). The annual drought series shows the strongest SNR of any variable analysed in the project and was therefore examined in further detail.

Because PET is estimated from temperature, the County Wexford temperature record used here was compared with the long-term temperature dataset compiled by Mateus and Potito (2022). Both series show a marked increase in temperature beginning in the late 1980s, indicating consistency between datasets and increasing confidence in the robustness of the results.

Overall, the results provide clear evidence of a climate change signal in increased evaporative demand for drought conditions in County Wexford. The wider interpretation of climate change impacts on drought, however, requires some nuance. Precipitation remains the primary driver of drought occurrence, and no clear evidence was found of a climate change signal in precipitation itself. Although summer rainfall shows a declining trend, the analysis does not support the attribution of that trend to anthropogenic climate change. Instead, the results suggest an interaction between natural climate variability and anthropogenic warming. In this case, a climate change signal in evaporative demand appears to amplify drought severity, particularly when natural variability also acts to reduce summer rainfall. Even at the annual scale, where precipitation trends may act to reduce drought likelihood overall, drought events that do occur are intensified by higher evaporative demand associated with climate change. Taken together, these findings indicate that, while the link between precipitation trends and anthropogenic climate change remains uncertain, warming-driven evaporative demand is already altering drought characteristics in County Wexford (Figure 4.2).

## 4.5 Assumptions and Limitations

This analysis assumes that long-term climate series provide a credible basis for assessing drought emergence and attribution, and that relationships with GMST can be interpreted as approximately linear over the observed range. The findings are region specific and extending such investigations to other parts of Ireland should be a priority for future research, given the implications. Earlier parts of the temperature record are more uncertain because they rely on bias-adjusted 20CR reanalysis infilling, and PET is estimated using the Oudin method, so the results may be sensitive to the PET formulation adopted. The Oudin method is potentially more sensitive to temperature changes than more complex methods that consider additional meteorological parameters. Comparison with a quality-assured and independent long-term temperature series increases confidence in the main warming signal. The study focused on meteorological drought indicators and did not directly quantify hydrological, ecological or water supply impacts.

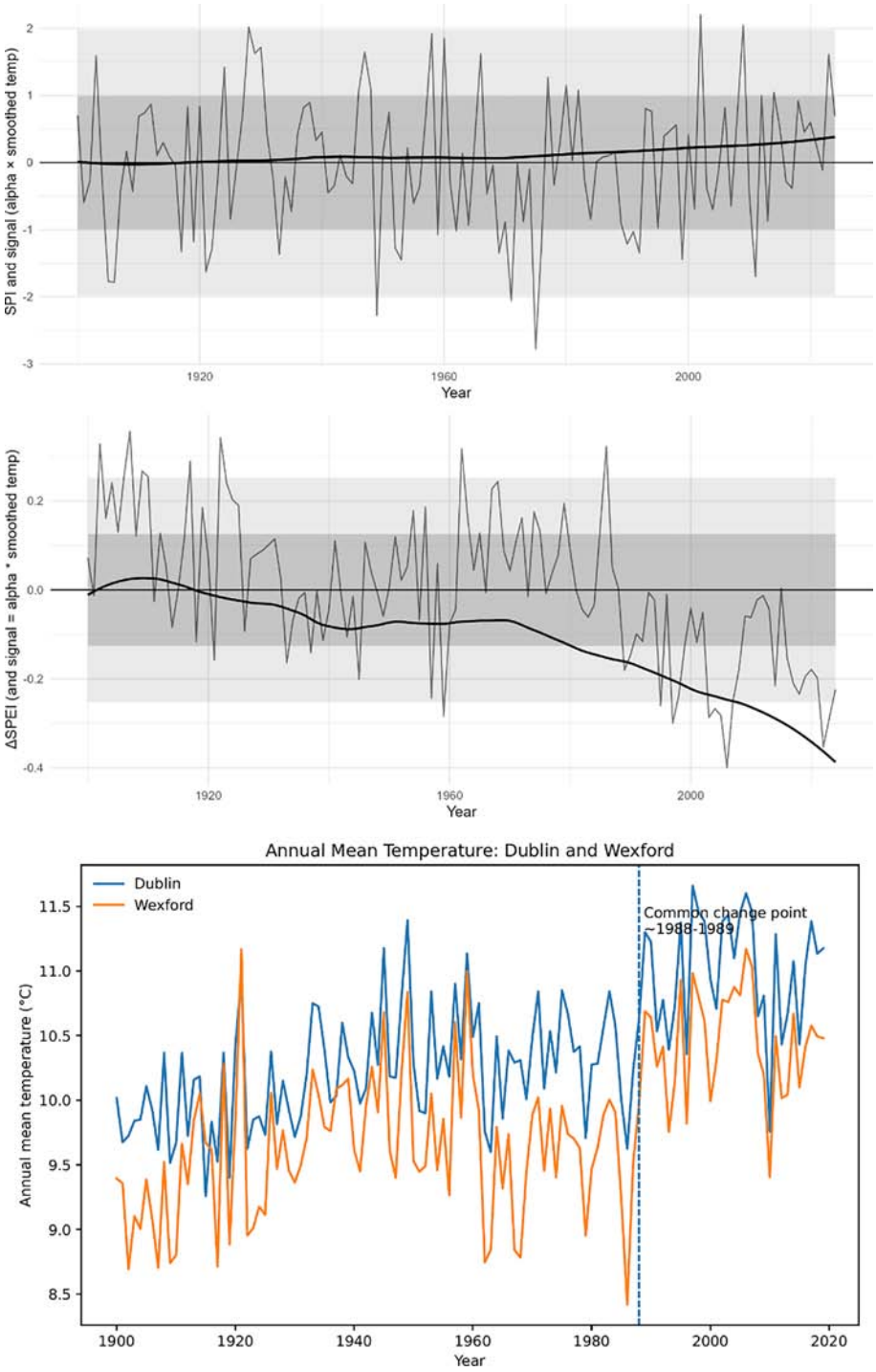



**Figure 4.2. Top panel: annual SPI series for County Wexford showing weak increasing trend (towards less severe droughts) and the lack of emergence of a climate change signal (SNR < 1; dark-grey shading). Middle panel: annual ΔSPEI series showing strong decreasing trends (towards more severe droughts), with the SNR emerging beyond 3 standard deviations (light-grey shading). Bottom panel: comparison of annual temperature series for County Wexford and County Dublin, showing consistent increases in temperature via a step change in the late 1980s.**

## 4.6 Key Messages and Policy Implications

- Evaporative demand is already intensifying drought severity. The clearest detected and emerged signal is in evaporative demand (ΔSPEI) rather than the SPI. This means that warming is making drought deficits more severe through higher atmospheric demand for moisture, even though precipitation trends alone do not show a clear climate change signal.
- Precipitation-only drought indicators can understate climate risk. Because the SPI does not capture the effect of rising evaporative demand, reliance on precipitation-only monitoring may underestimate the severity of drought under present and future warming conditions. Monitoring frameworks should incorporate indicators sensitive to both rainfall deficits and rising evaporative demand.
- Warming amplifies drought severity even though rainfall variability is natural. Summer rainfall shows a declining trend, but this trend was not found to be attributable to anthropogenic climate change in this analysis. The practical implication is that natural variability can amplify the effects of warming-driven increases in evaporative demand, producing more severe impacts.
- Adaptation planning should focus on the severity as well as the frequency of occurrence of drought events. Even if annual precipitation does not decline, drought events that do occur may become more damaging because soils, vegetation and water supplies are subject to greater evaporative losses. Planning for agriculture, water resources and drought preparedness should therefore focus on event severity, duration and cumulative deficit, not just frequency.
- Continued warming over the coming decades will further increase evaporative demand. Long-term, quality-assured and updateable local records are essential for tracking change and assessing sensitivity. The bespoke County Wexford precipitation and temperature series developed as part of this case study provide a practical foundation for operational drought monitoring, attribution-informed risk assessment and local adaptation planning. Similar long-term datasets would strengthen drought preparedness elsewhere in Ireland.

# 5 Midleton Floods: A Counterfactual Analysis

## 5.1 Case Study Overview

**Box 5.1. Midleton floods: case study overview**

**Hazard:** river flooding (event-based peak flow; Storm Babet).
**Region:** Midleton town/Owenacurra catchment, County Cork, south-west Ireland.
**Relevant sectors:** flood risk management, flood scheme design, emergency planning, climate adaptation.
**Period analysed:** October 2023 (specifically during Storm Babet), with long-term rainfall and GMST records being used for scaling.
**HydroDARE framework:** Pathway B (hydrological), with extension to counterfactual analysis.
**Primary policy relevance:** shows how an attribution framework can be used to stress-test a real flood event under conditions of further warming and support adaptation pathway triggers.
**Key finding:** the Storm Babet flood can be placed in a climate change context using observed rainfall–flood relationships, and the same framework can generate event-specific warming counterfactuals for planning and design review.

## 5.2 The Problem and the Policy Context

Storm Babet (October 2023) caused severe flooding in Ireland, with particularly damaging impacts in east County Cork (including Midleton), and is estimated to have caused around €200 million in damage. The event was driven by prolonged intense rainfall over already saturated catchments, which led to rapid river rises; widespread overbank flooding; disruption to transport, water treatment and electricity supply; and inundation of hundreds of homes and businesses (Clarke *et al*., 2024). Storm Babet has highlighted a central policy challenge: how to use observed evidence to judge how similar high-impact events may change as warming continues. Traditional assessments often separate event attribution from adaptation planning, but flood managers need a bridge between the two. This case study applied HydroDARE Pathway B, for hydrological variables, to provide that bridge by linking GMST to flood-generating rainfall and then to peak October river flows (similar to previous case studies), and it extended the pathway to apply scaling factors to changes observed during a specific event. Therefore, the framework was used not only to describe the climate sensitivity of October floods in general terms but also to build an event-based warming counterfactual for a Storm Babet-type flood. A counterfactual is an evidence-based "what if" version of an observed event (Lin *et al*., 2020; Woo, 2022). Here, the observed Storm Babet flood was the reference event, and the framework was used to explore how a similar event might differ if it occurred in a warmer climate, while keeping the same physical pathway from warming to rainfall to peak flow. A physically plausible pathway is based on the Clausius–Clapeyron relationship: air can hold about 6–7% more moisture per 1°C of warming, so, for a storm with otherwise similar dynamics, rainfall totals would be expected to increase accordingly (Trenberth *et al*., 2003; Fischer and Knutti, 2016).

## 5.3 Detection and Attribution Approach

The analysis applied HydroDARE Pathway B and uses the same causal-chain logic used in the Shannon case study (Chapter 3) but applies it to October daily maximum flows for the Owenacurra catchment at Ballyedmond (s19020), upstream of Midleton, County Cork (Figure 5.1). The core steps remained the same as those used in the Shannon flood example: (1) assemble quality-assured discharge and precipitation data; (2) detect changes in observed flood series; (3) reconstruct flood behaviour from flood-relevant precipitation indices (causal chains); (4) partition climate-driven and internal/non-climatic components using model residuals; (5) test whether causal-chain precipitation indices show a

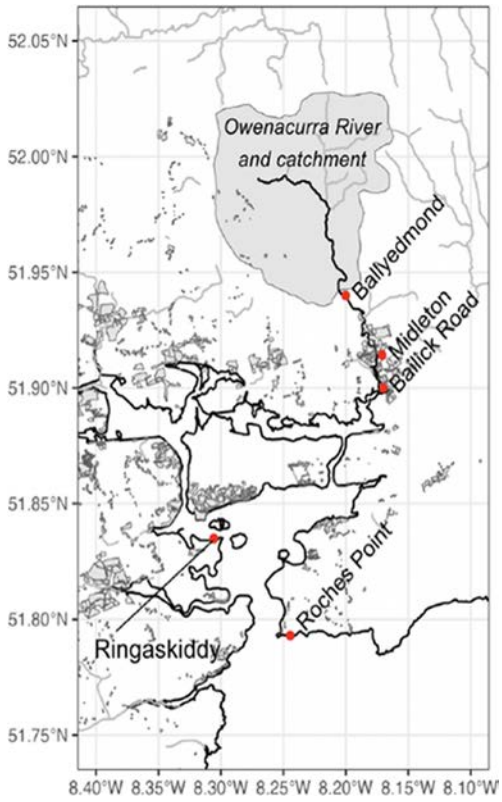



**Figure 5.1. Map of the study area, including the location of Midleton town, the Owenacurra catchment, the Ballyedmond discharge gauge and the long-term daily rainfall series at Roches Point. Source: Reproduced from Clarke *et al*., 2024; licensed under CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/).**

warming-related signal using GMST; and (6) propagate uncertainty to scale local flood sensitivity based on projected future warming. The key additional step included was the counterfactual extension of the framework to estimate how a specific flood event – that associated with Storm Babet – would differ under different global warming levels.

**Data sources and details of the event:** October maximum discharge at Ballyedmond gauging station (s19020) on the Owenacurra River (about 2.8 km upstream of Midleton) was used to represent the flood response, with the observed daily discharge series beginning in June 1977. Storm Babet (October 2023) produced the largest recorded discharge in this series, making it a suitable anchor event for the counterfactual analysis. Candidate flood-generating rainfall indicators were derived from Met Éireann's 1-km-gridded precipitation dataset (for catchment average rainfall over the Owenacurra River, concurrent with the discharge record) and from the long-term Roches Point daily rainfall record (1900–present), which is used for climate scaling over a much longer period.

**Causal chains and series reconstruction:** candidate rainfall indicators were tested in regression models to reconstruct the October maximum flood series and identify the most hydrologically relevant predictors of peak flow. This step established the local causal chain linking rainfall to flood magnitude and provided the coefficients needed for subsequent climate scaling and counterfactual analysis.

**Climate scaling:** after identifying the flood-relevant rainfall predictors from catchment data, the same indices were extracted from the long-term Roches Point record and regressed onto smoothed GMST anomalies (relative to 1850–1900) to test which parts of the flood pathway were climate sensitive. GMST data were derived from Berkeley Earth land–ocean temperatures combined with the Met Office Hadley Centre's sea surface temperature dataset HadSST4, obtained via KNMI Climate Explorer and smoothed using locally estimated scatterplot smoothing (LOESS) (span = 0.25) following the approach described by Hawkins *et al*. (2020).

**Event-based counterfactual generation:** a key extension of the framework in this case study was the generation of an event-based counterfactual for Storm Babet. Here, the counterfactual looks at how a Storm Babet-type flood might differ if it occurred under higher GMST conditions. The counterfactual was generated by scaling the GMST-sensitive rainfall component(s) based on higher GMST levels and propagating the change through the fitted rainfall–flood model, while holding non-GMST-sensitive rainfall components at observed 2023 values. Uncertainty was propagated through both the GMST–rainfall and rainfall–flood relationships using Monte Carlo simulation, producing a distribution of Storm Babet-like flood magnitudes under various warming conditions for adaptation stress-testing.

## 5.4 Key Results

### *5.4.1 Flood causal chain for the Storm Babet floods shows importance of rainfall intensity and catchment wetness*

The fitted flood model identifies a two-part flood-generating pathway for the October 2023 floods

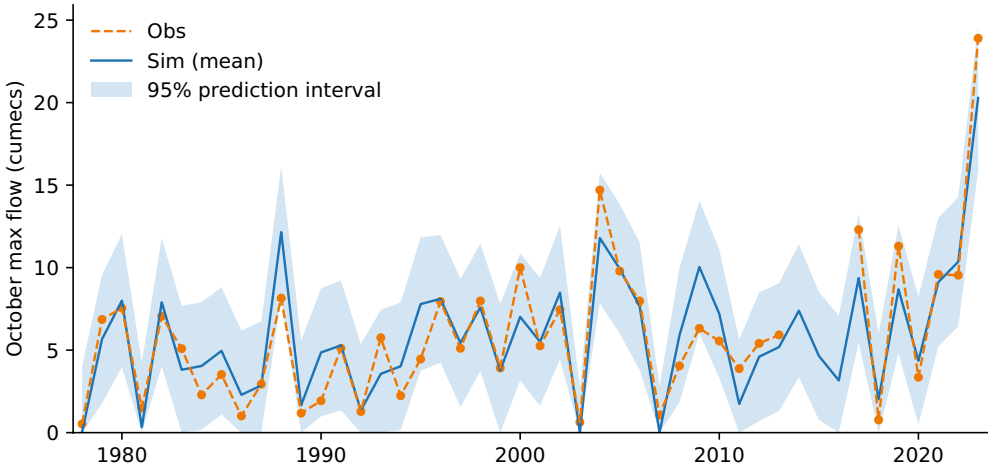



**Figure 5.2. Observed and simulated October maximum flood series at the Ballyedmond gauge for the period 1977–2023, with 95% prediction intervals. Cumecs, cubic metres per second; Obs, observed; Sim, simulated.**

at Ballyedmond, combining the October RX5day total (trigger rainfall) and cumulative rainfall total in the period July–October (JASO) (antecedent conditions). This confirms that Storm Babet-scale flooding reflects both event rainfall intensity and prior catchment wetness, rather than trigger rainfall alone. The two-predictor reconstruction captures the observed October flood series well (adjusted $R^2 = 0.82$), indicating that the selected rainfall indicators provide a physically coherent and statistically robust representation of flood generation in the catchment (Figure 5.2).

### 5.4.2 *Event rainfall intensity is the climate-sensitive part of the pathway*

The climate-scaling analysis shows that the strongest warming-linked signal is carried by the trigger rainfall component. October RX5day totals have a significant positive relationship with GMST ($p = 0.02$; +10.23 mm per 1°C increase in GMST; standard error = 4.49 mm), indicating that the rainfall process most directly associated with triggering flooding is climate sensitive. By contrast, although JASO is hydrologically important for flood generation, it is not significantly related to GMST over the long-term record. However, JASO in 2023 was the highest on record at Roches Point (since 1900), highlighting the exceptional antecedent wetness conditions associated with Storm Babet (Figure 5.3).

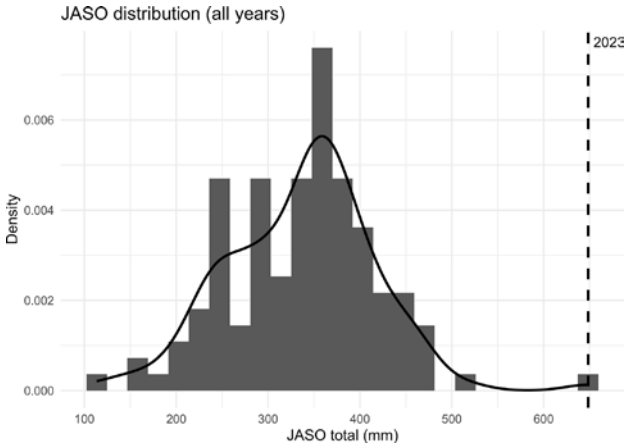



**Figure 5.3. Distribution of JASO at Roches Point for the period 1900–2023, indicating the extreme nature of JASO in 2023.**

### 5.4.3 *Event-based counterfactual: how might Storm Babet-type floods differ in a warmer climate?*

Using the GMST-sensitive rainfall pathway, the case study generated a future-warming counterfactual for Storm Babet. Rather than constructing a different storm, the method used the observed Storm Babet event as the reference and asked how the fluvial flood peak would differ if a similar event occurred under warming beyond 2023 conditions, with the change transmitted through the climate-sensitive trigger rainfall pathway (October RX5day totals) and antecedent JASO being held at its observed 2023 value. Assuming

approximately 1°C of global warming had already occurred by 2023 relative to the early industrial period, the simulations indicate that GMST-driven increases in October RX5day totals would increase the 2023 Storm Babet flood magnitude by approximately:

- 2.3% for 0.5°C of additional warming (95% range: 0.3–4.4%);
- 4.5% for 1.0°C of additional warming (95% range: 0.6–8.9%);
- 9.1% for 2.0°C of additional warming (95% range: 1.3–17.8%).

Expressed in rainfall terms, the same counterfactual implies increases in the October RX5day trigger of approximately 3.9% (+0.5°C), 7.7% (+1.0°C) and 15.4% (+2.0°C) relative to the 2023 event context. This is the key methodological advance demonstrated by the case study: the HydroDARE framework can move beyond providing generic flood sensitivity estimates to producing an event-based stress test that translates additional warming into changes in a known damaging flood. This creates a direct bridge between attribution and adaptation by translating plausible near-term warming increments into expected changes in a known damaging event. This method could be updated rapidly as new flood and rainfall observations become available, allowing agencies to reassess expected event amplification and review whether design assumptions, freeboard allowances or staged interventions will remain adequate under evolving warming. While the climate-sensitive trigger rainfall (RX5day totals) can be associated with warming, antecedent wetness (JASO) remains a major factor influencing flood magnitude and was already exceptionally high in 2023. The counterfactual estimates should therefore be read as warming-driven amplification of a Storm Babet-type event under similarly severe antecedent conditions, rather than a full projection of all flood-generating processes.

## 5.5 Assumptions and Limitations

This case study assumed that the rainfall–flood relationship identified for the Owenacurra catchment can be used to scale a Storm Babet-type event approximately linearly with warming through the GMST-sensitive rainfall pathway. As in Chapter 3, the analysis depended on transferring causal chains identified from catchment-based rainfall and flow data to a much longer-term rainfall record in order to assess climate sensitivity. However, the counterfactual varied only the thermodynamic, GMST-sensitive component of the event and did not vary the dynamical component, such as the circulation pattern or storm track that produced Storm Babet. Nor did this analysis include changes in sea level or tidal surge that may influence flood inundation extents in Midelton town. The resulting estimate is therefore useful for stress-testing for Storm Babet-type fluvial flood events under similarly extreme antecedent conditions, rather than providing a complete representation of how all processes shaping future flood risk may change.

## 5.6 Key Messages and Policy Implications

- The Storm Babet case study shows how the HydroDARE framework can be extended from attribution to producing a practical counterfactual and storyline stress-testing tool. The case study used observed GMST–rainfall–flood relationships to build an illustrative storyline for a future event (a Storm Babet-type flood in a warmer climate) and estimated how much greater in magnitude a similar flood event would be under additional warming. Such estimations are often more useful for decision-makers than abstract trend metrics alone, because they can be applied directly for testing flood schemes, making design assumptions and planning interventions.
- In the Owenacurra catchment, the October maximum flow series can be explained by a combination of short-duration heavy rainfall (October RX5day totals) and antecedent rainfall (JASO), with RX5day totals showing the clearest relationship with GMST. JASO remains critical for determining flood magnitude, and 2023 antecedent conditions were exceptionally wet, so the counterfactual should be read as the warming-driven amplification of a Storm Babet-type event under similarly severe antecedent conditions.
- Assuming ~1°C of warming had already occurred by 2023, the analysis indicates that a Storm Babet-type flood could be amplified by about 2.3% for 0.5°C, 4.5% for 1.0°C and 9.1% for 2.0°C of additional warming (with varying uncertainty ranges), giving decision-makers a direct way

to test scheme adequacy against plausible warming increments.

- Flood impacts do not scale linearly with peak flow, so flood extent modelling would be a valuable next step. Once key thresholds are crossed (e.g. defence overtopping, property floor levels or infrastructure inundation thresholds), even modest increases in a Storm Babet-type peak flow could result in disproportionately more damage and disruption. The counterfactual flow estimates from this analysis can be used directly as inputs for flood extent/inundation modelling, to test how additional warming could change flood depth, extent and exposure in Midleton.
- During Storm Babet, peak river flows coincided with a spring low tide, which helped drainage; if a similar event coincided with higher tides or surge conditions, impacts could be worse because of fluvial–coastal compound flooding.

# 6 Conclusions and Recommendations

## 6.1 Synthesis of Key Conclusions

The HydroDARE project has shown that detection and attribution can be made operational and transparent and can be relatively rapid to deploy using methods that work despite real-world Irish data constraints. The framework is intentionally modular, so it can be applied to meteorological variables directly or extended to hydrological variables where reconstruction and residual analysis are needed to separate external climate influences from internal catchment and observation system changes. This makes it a practical tool for answering a range of adaptation and catchment management questions, while keeping uncertainty explicit and relevant for decision-making. Importantly, the framework, supporting methods and case study workflows are available for reuse, which increases the potential for application in future projects and in operational climate services.

The operational implementation of the HydroDARE framework would require quality-assured long-term meteorological and hydrometric records, station metadata, catchment descriptors and information on internal catchment changes such as changes in drainage, land use, abstractions or engineering works. The analysis could be led collaboratively by Met Éireann, the OPW, the EPA, local authorities and sectoral bodies, and updated periodically, for example every 5 years, to support adaptation planning, with targeted updates being made following major flood or drought events or the release of improved datasets.

A central conclusion of the project is that data rescue and quality-assured long-term records are foundational for the detection and attribution of hydrological change and informing climate change adaptation and catchment management. Many of the advances achieved in the HydroDARE project were only possible because rescued and curated meteorological and hydrometric records were available to lengthen the observational baseline, improve spatial coverage and allow more robust testing of trends, step changes, emergence and causal links. We therefore emphasise that continued investment in monitoring, quality control, metadata, archiving and recovery of historical records should be seen not as peripheral to adaptation planning or useful only for understanding past change, but as essential for attribution and understanding future risks.

Across the case studies, we have shown that human-driven climate change is already an important driver of hydrological change in Ireland. For floods, warming is expressed through changes in flood-generating rainfall, particularly heavier and more persistent rainfall events that enhance flood risk via antecedent conditions and flood-generating events. For droughts, the clearest detected and emerged signal is in the increased evaporative demand associated with higher temperatures. Taken together, the case studies show that warming is acting through two key pathways that are highly relevant in terms of their impacts: intensification of heavy rainfall and intensification of atmospheric moisture demand.

The project has also shown that climate change does not act in isolation. The Wexford County drought case study (see Chapter 4) is especially instructive in this regard. The evidence suggests that summer rainfall reductions are more consistent with natural climate variability than with a clear anthropogenic climate change signal, while warming-driven increases in evaporative demand are clearly linked to climate change. The practical outcome is that drought severity is amplified by the combination of both components, with natural variability reducing rainfall at the same time as climate change increases evaporative losses. This is a critical point for consideration in adaptation planning. Current climate change risk assessments often focus mainly on the climate change signal, but robust adaptation planning needs to consider both the externally forced signal and the role of natural variability, especially where the latter can amplify impacts.

A key strength of the HydroDARE framework is the use of causal chains to identify the physically meaningful pathways linking large-scale climate drivers to local hydrological outcomes. In practical terms, this helps reveal which indices matter most for monitoring and planning. In the flood case studies presented in Chapters 3 and 5, for example, multi-day rainfall accumulations and other flood-generating rainfall

indicators emerge as the key variables linking warming to flood magnitude. This is important because it offers a route to making climate services more focused on impact-related variables and helps identify which metrics should be prioritised in future monitoring, assessment and climate service development.

For hydrological variables, an important methodological contribution of the project is the framework's use of reconstruction to partition external and internal changes, with the intent being not simply to fit a model but to use parsimonious, physically based reconstruction and residual diagnostics to separate the component of change that is consistent with climate inputs from the component that reflects internal catchment change or observation system inhomogeneity. This is important from a practical point of view because it means that internal change can also be investigated and, in some cases, its cause attributed using metadata and independent evidence. At the same time, the project findings highlight a national limitation: while hydrometric metadata can be extremely valuable in interpreting residual structure, there remains a lack of long-term, quality-assured datasets on land use and land management change at the catchment scale. This gap limits the extent to which internal drivers can be assessed consistently across Ireland.

The project has also shown that, where a credible link to anthropogenic climate change has been established, the methods can move beyond attribution to scaling and the development of counterfactual studies that investigate how recent extreme events would be expected to differ if they occurred in a warmer climate. Observed relationships can be translated into sensitivity to continued warming, making the framework useful not only for explaining recent events but also for adaptation planning. The Midleton/Storm Babet case study (see Chapter 5) shows how the framework can be extended to event-based counterfactual analysis, providing a practical way to stress-test a damaging event in a warmer climate. This gives agencies a direct route from observed change to attribution to decision-relevant estimates of how risks may evolve.

Finally, it is important to emphasise that the lack of evidence for a climate change signal does not imply the absence of such a signal, just that it cannot be detected in the data available. In noisy hydrological records, externally forced change may be present but not yet distinguishable from background variability at the required confidence level. This is where UNSEEN-type approaches (Kelder *et al*., 2020) could add value in future work. In summary, UNSEEN methods use large ensembles of physically plausible model simulations to generate many more realisations of the current climate than are available in the observed record alone. This helps to characterise the range of natural variability, assess rare but plausible events that may not appear in the observed record and explore whether an underlying climate change signal may already be influencing risk even though it has not yet clearly emerged from noise in observations (e.g. Chan *et al*., 2025). Used alongside the HydroDARE framework, such methods could strengthen future assessments of natural climate variability and plausible maximum extremes, together with emergence and adaptation thresholds in highly variable Irish hydroclimatic records.

## 6.2 Policy Recommendations and Future Work

- The evidence in this report shows that human-driven climate change is already impacting important components of hydrological risk. This means that approaches to flood and water management that continue to rely implicitly on stationarity may no longer be sufficient in all settings. Adaptation planning should therefore proceed with greater urgency and should explicitly consider both anthropogenic climate change and natural climate variability in risk assessment.
- The potential for implementing the HydroDARE framework as a practical operational approach in climate services, catchment management and adaptation planning should be investigated. Its modular structure, transparent logic and reliance on relatively simple statistical and reconstruction methods make it comparatively easy to apply where suitable data exist. The availability of the case study workflows should further support its uptake, reproducibility and extension in future work.
- The HydroDARE approach should be used to make climate services more focused on impact-related indicators. One of the clearest benefits of the causal-chain method is that it helps identify the variables that most directly connect climate

change to management-relevant outcomes, such as multi-day rainfall totals for flooding or evaporative demand-sensitive drought indicators. Future services should build on this by monitoring and communicating information on the variables that matter most for impacts, rather than relying on only broad averages or generic climate indicators.

- Where robust observational evidence links hydrologically relevant variables to anthropogenic warming, empirically derived scaling relationships should be developed and used in parallel with climate model projections. This is justified because empirical scaling provides a direct, observation-based estimate of local sensitivity to warming, grounded in the variables that matter most for impacts. It also offers an important line of evidence against which model simulations can be checked. Recent work for the UK shows that observed winter precipitation scaling can exceed the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble mean, implying that models may understate the rate at which flood-relevant rainfall intensifies with warming (Carruthers *et al*., 2026). Used together, empirical scaling and model simulations provide a stronger basis for adaptation planning than either approach alone. Models are essential for exploring spatial patterns, scenarios and physically plausible futures, while empirical scaling helps ensure that planning is anchored in observed change, impact-relevant causal chains and locally realised sensitivity to warming.
- Agencies such as the OPW are deploying adaptation pathways for monitoring and managing climate change adaptation. A key challenge in implementing such approaches is the identification of adaptation tipping points. Adaptation tipping points arise when an existing policy, measure or design standard no longer provides an acceptable level of performance as climate risk changes. Adaptation pathways respond to this by sequencing actions over time and defining trigger points for when additional measures are needed. The HydroDARE framework can support this by linking warming to impact-relevant variables through causal chains and scaling observed changes relative to a chosen baseline, helping to identify when thresholds may be approached or crossed. The framework can also be used to develop counterfactual storylines detailing physically plausible “what if” versions of observed damaging events in a warmer climate. These can provide practical, place-based stress tests for flood schemes, water systems, infrastructure and staged adaptation options.
- Future work should extend the framework beyond case studies to island-wide analyses, which was beyond the scope of the present project. The case studies presented here demonstrate proof of concept and policy relevance, but a fuller national application across a wider range of catchments and hydroclimate and monitoring contexts would provide a much stronger evidence base for national adaptation planning. Related work should also extend the framework to ungauged catchments by relating signals to catchment descriptors and to other extremes, including extreme heat and compound events, where causal-chain approaches may likewise help identify the most relevant impact pathways and monitoring variables.
- The findings of this project show that robust detection, attribution and scaling of hydrological change depend fundamentally on long-term, high-quality rainfall, temperature and flow records, supported by well-documented metadata. Without such records, it becomes far more difficult to distinguish climate-driven change from natural variability or internal catchment influences. The continued rescue, digitisation, quality control and curation of historical meteorological and hydrometric records should therefore be treated as a core adaptation priority and an essential foundation for future climate risk assessment, climate services and evidence-based water management.
- Efforts to better understand internal catchment change should prioritise the development of long-term, quality-assured land use and land management datasets at the catchment scale. The HydroDARE project has shown that internal change can, in principle, be assessed and attributed to a specific cause, especially where residual diagnostics can be tested against metadata and independent evidence. However, doing this consistently remains difficult in Ireland because suitable national datasets are limited. Improving this evidence base would materially strengthen approaches for the attribution of hydrological change.

- The findings of this project suggest that arterial drainage can amplify the flood signal associated with climate change by increasing the efficiency with which flood-generating rainfall is translated into peak flows, thereby increasing downstream risk. Future flood risk assessment and adaptation planning should therefore explicitly consider how arterial drainage alters catchment sensitivity to heavier rainfall under a warmer climate, and whether current maintenance and management approaches remain appropriate where they may reinforce climate-driven increases in flood hazards.
- Future climate risk assessment and adaptation planning should place stronger emphasis on the combined role of climate change and natural climate variability. The County Wexford case study (see Chapter 4) shows clearly that impacts can be amplified when a warming-driven signal unfolds alongside naturally occurring reductions in rainfall. Adaptation planning should therefore seek to quantify both components, rather than considering the anthropogenic climate change signal alone. This is especially important for drought and other hazards where variability remains large relative to the forced trend.
- Finally, in future work, the HydroDARE framework should be linked with methods such as UNSEEN, which could help characterise the range of plausible natural variability and assess whether climate change signals may already be present in noisy records before formal emergence thresholds have been crossed. This would help strengthen planning for rare extremes, improve interpretation of non-emerged signals and support more robust adaptation in a highly variable hydroclimatic setting.

## 6.3 Final Remarks

The findings of the HydroDARE project demonstrate that attribution methods can be made more practical, more transparent and more useful for Irish policy and practice. The project has shown that a warmer atmosphere is already altering important components of extreme rainfall, flood and drought risks, while also demonstrating that natural variability and internal catchment change remain essential parts of the story. By combining long-term records, data rescue, quality assurance, causal chains, reconstruction and scaling, the project has developed a usable framework not only for explaining observed change, but also for quantifying sensitivity to future warming and supporting adaptation planning in a non-stationary climate. The project's wider value lies not only in the individual case studies, but in establishing an approach that can now be extended, applied more widely and used to build more focused and decision-relevant climate services for Ireland, including through the use of counterfactual event storylines to explore future extremes and stress-test adaptation pathways.

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# Abbreviations

| | |
|---|---|
| **20CR** | Twentieth Century Reanalysis |
| **ΔSPEI** | Index based on the difference in SPEI derived using average monthly PET and SPEI derived using observed PET series |
| **GMST** | Global mean surface temperature |
| **IAMAX** | Instantaneous annual maximum |
| **JASO** | Cumulative rainfall total in the period July–October |
| **OPW** | Office of Public Works |
| **PET** | Potential evapotranspiration |
| **SDII** | Simple Daily Intensity Index |
| **SNR** | Signal-to-noise ratio |
| **SPEI** | Standardised Precipitation–Evapotranspiration Index |
| **SPI** | Standardised Precipitation Index |
| **RX5day** | Maximum consecutive 5-day precipitation |
| **RX30day** | Maximum consecutive 30-day precipitation |

# 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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