Projected climate change in Ireland and associated risk to water quantity; a review of national policies, governance and plans for future proofing Ireland's water supply

Dr Fiachra O'Loughlin & Mr. Behzad Mozafari

Dooge Centre for Water Resources Research

School of Civil Engineering

University College Dublin

Table of Contents

Executive Summary

The latest IPCC 6th Assessment Report (AR6) highlights that climate change is already having significant impacts globally to varying amounts. It also highlights that if warming reaches 1.5^{O}C it will result in unavoidable increases in extreme events, e.g. floods and droughts.

For Ireland, climate change will have two major trends related to water quantity: 1) temperatures will increase with a clear spatial pattern; and 2) the frequency of extreme events will increase. Research shows that by the mid-century temperatures will be between 1 ^{O}C and 1.6 ^{O}C warmer compared to 1975-2005 but that the East coast will experience larger increase. Research also indicates that while the annual average temperatures will increase, Summer and Autumn temperatures will see the largest increase with increases in excess of 3 ^{O}C possible in Autumn by 2100.

As temperatures increase, extreme events will also become more frequent. Leahy et al. (2021) highlighted this and noted both regional droughts and large flooding events will become more common. Fealy et al. (2018), Nolan and Flanagan (2021) and Leahy et al. (2021) all note that extended dry periods (5 days with less than 1 mm of precipitation) will become more common due to climate change, with decreases up to 20% in Summer possible.

Ireland can also expect more frequent extreme precipitation and flooding (Fealy et al., 2018) and that the number of heavy (>20mm) and very heavy rainfall (>30mm) days will increase. The North-West will experience the worst of these increases. This may be due to the direct relationship between temperature and rainfall (Clausius-Clapeyron) where increases of up to 15% per 1^{o}C warming have been noted.

A review of the Climate Action Plan and relevant adaptation plans, highlights that the impact of climate change on water quantity is either not emphasised sufficiently or uses outdated outputs from climate models. In the Climate Action Plan 2021, only 7% of the listed Actions mention water quantity and an additional 25% of the Actions would benefit from the inclusion of water quantity to secure supply, protect life and property and increase awareness. The use of outdated model outputs in the sectoral plans also needs to be addressed. Uisce Éireann's National Framework Plan uses climate projections based on the IPCC's 4th Assessment Report (AR4) (two generations old) and the Flood Risk Management Plan of the Department of Housing, Local Government and Heritage, suggests using projections from prior to 2011. The latest projections are provided by more advanced models with updated emission scenarios and better understanding of climate processes are more accurate.

Across Ireland, seven organisations are responsible for collecting water level and flow and currently there are 1031 active stations. While these have a good spatial distribution, the record lengths are not sufficiently long enough for accurately modelling droughts, as only 17 stations have 75 years or more data and only ~30% have record lengths greater than 50 years.

An analysis of annual average discharge change from hydrological models obtained from https://cds.climate.copernicus.eu/ highlight the need for the impact of climate change to be investigated on the catchment scale and not regional. The simulations show that irrespective of the Representative Concentration Pathway (RCP) of greenhouse gas concentrations, Ireland will be drier in the future, with the East and South-East more severely impacted. Under RCP 8.5, most of Ireland could be 10% drier by 2100 and some catchments could experience flow reductions close to 30%.

Based on the review of the literature, Climate Action Plan, Sectoral Plans and existing data, several policy recommendations have been made under different headings.

Water Policy

- Ireland's Climate Action Plan should include water quantity in Climate Action Planning.
- Future revisions of the National Development Plan and Housing for All Plan should include water efficiency targets.
- Revisions of the Flood Risk Management Plan should include the latest scientific data on future projections for Ireland and details of assessment and management and investment requirements.

Management and Governance

- **Ireland needs to develop a National Climate Change Risk Assessment** to help highlight where adaptation measures have not kept pace with the latest climate change projections and inform the identification of new adaptation measures.

Water Resource Planning

- The National Hydrometric Working Group should ensure longevity in monitoring stations across a range of catchment sizes throughout the country going forward.
- Integrated catchment management and water resource planning is needed to ensure the security of supply. This is also a recommendation of the Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan.
- Drought Management Plans should be developed and published for every water resource zone.
- A Registry of Extreme Events is needed to help understand disaster risk and is required under the UN Sendai Framework for Disaster Risk Reduction.
- More advance methods are needed for the modelling of the impact of climate change on floods and droughts at catchment scale.

Risk Communication

- Education is key for risk communication. This could be addressed through updates of the Climate Action Plan.

1. Introduction

According to the IPCC Sixth Assessment Report human induced climate change is already having widespread serious impacts globally that cannot be explained by natural climate variability (Pörtner et al., 2022a). While climate change will not impact everyone and everywhere equally, the current best knowledge and data highlights that if warming reaches 1.5 ^{O}C in the near-term there will be significant and unavoidable increase in hazards (e.g. floods, droughts, wildfires). Across Europe, the IPCC noted four key risks that will be faced due to climate change:

- Key Risk 1: Mortality and morbidity of people and changes in ecosystems due to heat
- Key Risk 2: Heat and drought stress on crops
- Key Risk 3: Water scarcity
- Key Risk 4: Flooding and sea level rise.

Key Risks 3 and 4, Water scarcity and Flooding and sea level rise are of particular relevance to this study. Under this risk, the IPCC highlights that across Europe (mostly Southern and Western Central Europe) one third of the population will be exposed to lack of water with 2 ^{O}C warming and that many cities will be impacted. While we know this for mainland Europe, it is still not fully understood how Ireland will be impacted.

This research aims to provide a better understanding of how Ireland and it's water resources will be impacted by future climate change. The report is presented in six sections, listed below, that aims to improve our understanding of climate change and water quantity in Ireland, identify challenges, and propose policy recommendations to better prepare for climate change.

- Review of current state of the art on climate change and water quantity (Section 2)
- Review of the national policies (Section 3)
- Review of the Irish national hydrometric monitoring stations (Section 4)
- Change in Water Quantity across Irish catchments (Section 5)
- Discussion and Conclusions and Recommendations (Section 6)

2. Current State of Knowledge

The IPCC Sixth Assessment's Summary report for policymakers (Pörtner et al., 2022a) has highlighted that climate change has already had a significant impact on the global climate system. The report noted that anthropogenic (human influenced) climate change has already caused global land surface temperatures to rise more than 1^{O}C since 1850-1900. The evidence highlights that the current changes are unprecedented with temperatures rising faster since 1970 than in history. A similar pattern is clear with precipitation where evidence shows that global average precipitation has increased since 1950 and both the frequency and intensity of heavy precipitation events have increased since the 1950s.

This summary report also describes what the future climate will look like. Even if greenhouse gas emissions (GHGs) are significantly reduced, global surface temperatures will increase until mid-century. If GHGs are not reduced to sufficient levels 1.5 ^{O}C and 2 ^{O}C warming thresholds will be exceeded during this century. This will have a significant impact on the likelihood of extreme events occurring. In a 1.5 ^{O}C warmer climate, heavy precipitation events and droughts (with a 10-year return period) are 1.5 and 2 times more likely to occur. In a 2 ^{O}C warmer planet, these events will be 1.7 and 2.4 times more likely to occur.

In the sixth assessment, the globe is divided into 11 regions and four cover Europe, with Ireland included in the Northern European region (NEU). NEU covers the following area: Ireland, United Kingdom, and the Scandinavian countries. While the global picture suggests more frequent flooding and drought events in the future, looking the NEU, the sixth assessment suggests a 5% decrease in fluvial flooding (river flooding) but an increase in pluvial flooding (due to excess precipitation) and that the frequency and severity of low flows will decrease across the NEU region (Pörtner et al., 2022a).

Irish Context

While the global and European context hints at what Ireland may experience due to climate change, they also show potentially different outcomes, highlighting that the scale at which climate change is looked at is critically important. Therefore, it is necessary to review the existing peer-reviewed literature specific to Ireland to ensure that the full extent of climate change on Irish water quantity can be determined. A review of all relevant publications from the Irish Environmental Protection Agency, Met Éireann, ICARUS Climate Research Centre and on Scopus was performed. Scopus is the largest database of peer-reviewed literature, and the following terms were used to identify potentially suitable literature:

- "Changing climate" or "climate change*"
  and
- "Water"
  and
- "Ireland" or "Irish"

By combining all relevant publications two common trends that will have an impact on Ireland's water quantity were identified.

Trend 1: Temperatures will increase across the entire island but there will be a spatial pattern

Nolan and Flanagan (2021) looked at high-resolution climate projection for Ireland as part of an EPA project using a multi-model ensemble approach. Their results highlighted that by the middle of this current century it is expected that the average temperature across Ireland will have increased by between 1 ^{O}C and 1.6 ^{O}C from the baseline period (1975- 2005), depending on which Representative Concentration Pathway (RCP) is used, with the larger increase associated with RCP8.5 and the lower with RCP4.5. Their analysis demonstrated a significant spatial pattern across the island of Ireland, with the East Coast experiencing higher temperature increases compared with the West Coast. Their results supported the work of Fealy et al. (2018) who used coarser spatial resolution data and noted that by the end of the 21st Century temperatures across Ireland could be between 0.5 ^{O}C and 4.5 ^{O}C higher than the baseline. However, the lower increase in temperature of0.5 ^{O}C, is associated with RCP2.6 which is no longer feasible due to the delay to act on results from the IPCC and reduce GHG emissions. While Nolan and Flanagan (2021) noted a spatial pattern in temperature increases across Ireland, the work of Fealy et al (2018) discovered a significant seasonal pattern. They found that all seasons will experience increases in temperature; however, Summer (June, July, August) and Autumn (September, October, November) will see the largest increases with 3.1 ^{O}C warming expected during Autumn by the end of the Century (2071-2100) under RCP8.5. A direct impact of increasing temperature is the corresponding increase in evapotranspiration, the amount of water evaporated and transpired from plants. Gharbia et al. (2018) found the potential evapotranspiration (PET) will increase with climate change and that for the Shannon River Basin this could result in the PET being 13.5% larger in 2080 than today.

Trend 2: The frequency of extreme weather events will increase

For this subsection the term extreme weather events refers to changes in precipitation and corresponding changes in river discharge. While Trend 1 shows that there will be a significant increase in temperature expected across Ireland, Trend 2 indicates this will occur while precipitation patterns are also undergoing significant change. Leahy et al. (2021) noted in their EPA project "ClimAtt: Tools for Climate Change Attribution of Extreme Weather Events" that these events will become more frequent and will result in both regional droughts and large flooding events becoming more common. This means that Ireland will be forced to deal with both extremes in water quantity (too little and too much) more regularly.

There is complete agreement across scientific studies that extended dry periods, of 5 plus days with less than 1 mm of precipitation recorded, will become more common in Ireland due to climate change (Fealy et al., 2018; Nolan and Flanagan, 2021; Leahy et al., 2021). Fealy et al. (2018) highlighted that Ireland could be faced with large decreases, in the range of 5.5% and 13.7%, in Summer (JJA) precipitation by the end of the century. Nolan and Flanagan (2021) found a similar decrease in Summer precipitation (3 to 20%). Leahy et al. (2021) notes that extended dry periods will become more common due to climate change and that by mid-century these will be in the range of 11% and 48% more frequent during the summer months.

While Ireland will experience less precipitation over the entire year (Nolan and Flanagan, 2021), especially during the summer months as previously mentioned, more frequent extreme precipitation and flooding is also expected. Fealy et al. (2018) noted that while the number of wet days will decrease due to climate change, there will be an increase in the number of heavy and very heavy rainfall events. These are days when rainfall is in excess of 20 and 30 mm respectively. The North-West of Ireland is expected to experience the worst of these increases with the occurrence increasing by 30%. Other coastal areas will also experience larger than average increases in occurrences while the Midlands will experience fewer heavy rain days.

This change in the number of heavy and very heavy rainfall days will have a direct impact on flows in Irish rivers. Several studies have looked at what this would mean for river discharges and flood risk (Bastola et al., 2011; Kirkpatrick and Olbert, 2020; Meresa et al., 2021, 2022; Sarkar Basu et al., 2022). All studies show that higher flows are expected in winter and this corresponds to an increased flood risk. Sarkar Basu et al. (2022) predicts that for the Dodder River basin annual maximum flows could increase by between 12% and 16% for 50- and 100-year return periods. This finding supported the work of Bastola et al. (2011) who noted that the impact of climate change will not be the same for all flood return periods. As river flood risk is increasing, there will also be changes in groundwater and urban flooding. Morrissey et al. (2021) noted that for lowland karst systems on the West Coast flood levels will increase for events equal to or larger than the mean. In urban regions flood risk will also increase and Willuweit et al. (2016) found that urban runoff in Dublin could increase by 30% in the winter months.

Fewer studies have looked at the impact of climate change on low flows or on water supply compared with flooding However, those that did (Charlton et al., 2006; Hall and Murphy, 2010, 2011; Meresa et al., 2022). all agree climate change will have a negative impact. Charlton et al. (2006) showed that effective runoff would experience a significant decrease across summer months due to climate change. Meresa et al. (2022) found that for 37 catchments across Ireland there will be large decreases in low flows during summer periods and that by the 2080s Q95 flows (lowest 5 percentile flows) will have reduced by approximately 21%. Hall and Murphy (2011) found that the impact of climate change is non-uniform. They found that up to the 2050s, climate change will not increase water stress corresponding to the median and higher discharges; however, that it will have a clear stress on low flows. They also highlighted that all catchments will behave differently and that there is a need for site specific analysis for water management plans.

Implication of trends on Ireland’s water quantity

The two trends discussed above will have a significant impact on Ireland’s water quantity going forward and the compounding effects of the trends should not be underestimated. Our water budget can be simplified into a water balance equation:

$$Q = P - ET \pm \Delta S$$

where Q is discharge, P is precipitation, ET is evapotranspiration (combination of evaporation and transpiration in plants) and ΔS is the change in water storage, across the time period of interest. The two trends identified in the review will directly affect the components of the above equation in various ways and at different timescales, in particular trend 1 temperature. Temperature is a critical factor that influences many aspects of the hydrological cycle. For example, there is a clear and direct relationship between temperature and evaporation and if the average temperature increases, the average evaporation rate will also increase. This leads to many secondary impacts such as lower soil moisture due to higher evaporation rates.

However, there is also a direct relationship between temperature and the volume of precipitation possible. This is called the Clausius-Clapeyron (C-C) relationship and studies have shown that heavy rainfall events increase by up to 15% per 1ºC warming. This is because the volume of precipitation possible is determined by the saturation vapour pressure, which increases with temperature. If we take the values of global warming previously mentioned and apply the 15% increase per 1ºC warming, then it is feasible that extreme rainfall events could be on average 15-22% larger than today by the end of the century (taking the 1 to 1.6 ºC warming suggested by Nolan and Flanagan, 2021). The seasonal picture is more extreme with increases greater than 4.5 times current values during Autumn by the end of the century (taking Fealy et al., 2018 estimate of 3.1 ºC warming during Autumn by end of century). These increases will not only lead to increased flood risk but have the potential to severely impact many sectors across Ireland, including agriculture.

Despite the increase in extreme rainfall events, overall, it is expected that Ireland will experience longer extended dry periods (Fealy et al., 2018; Nolan and Flanagan, 2021; Leahy et al., 2021), with less precipitation over the year (Nolan and Flanagan, 2021) and higher temperatures, droughts will become more frequent. However, as this is due to a shift in climate rather than a change in weather (short term), there is an increased risk that droughts will become more regular, longer and with potential for multi-year droughts, which are already being experienced in Europe. This is because the only way for water quantities to rebound to normal conditions is for wetter than normal conditions to occur. The more severe the drought the longer/ more extreme these wetter than normal conditions need to be for soil moisture, water tables and river and lake levels to rebound.

Key Points

- By the middle of this current century, it is expected that the average temperature across Ireland will have increased by between 1°C and 1.6°C from the baseline period (1975- 2005),
- All seasons will experience increases in temperature; however, Summer (June, July, August) and Autumn (September, October, November) will see the largest increases with 3.1˚C warming expected during Autumn by the end of the Century (2071-2100) under RCP8.5.
- Extended dry periods, of 5 plus days with less than 1 mm of precipitation recorded, will become more common in Ireland due to climate change.
- There is an increased risk that droughts will become more regular, longer and with potential for multi-year droughts.
- While the annual precipitation will decrease due to climate change, there will be an increase in the number of heavy and very heavy rainfall that occur (rainfall is in excess of 20 and 30 mm). The North-West of Ireland is expected to experience the worst of these increases with the occurrence projected to increase by 30%.
- All studies show that higher flows are expected in winter, and this corresponds to an increased flood risk, where annual maximum flows could increase by between 12% and 16% for 50- and 100- year return periods and urban runoff in Dublin could increase by 30% in the winter months.

3. Review of National Policies

A review of the following national policies is presented in this section to see how they discuss and plan to deal with climate change and water quantity:

- Government of Ireland's Climate Action Plan 2021
- Flood Risk Management – Climate Change Sectoral Adaptation Plan 2019
- Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan
- National Water Resources Plan - Framework Plan (Drought Planning)

The extent which each of the plans correlates with the existing stage of the knowledge on climate change and water quantity is also assessed.

Government of Ireland's Climate Action Plan 2021

The Climate Action Plan 2021[1] is the roadmap for meeting Ireland's 2050 national climate objective, with the overall aim to halve Ireland's greenhouse emission by 2030 and be net zero by 2050 at the latest. The Plan clearly states that:

> "The science is indisputable and the effects of climate change are already clear",

which agrees with the findings from the latest IPCC reports. The plan has 493 actions to help reach the overall aim and targets six main areas for reduction of GHG emissions:

- Electricity
- Transport
- Buildings
- Industry
- Agriculture
- Land Use, Land Use Change and Forestry (LULUCF)

Unsurprisingly, water quantity is seldom mentioned as this was not the main focus of the Climate Action Plan 2021. For example, terms related to water quantity such as: flooding is mentioned 37 times; drought is mentioned only 5 times and water supply mentioned just once. As previously shown, water quantity will be significantly impacted due to climate change and the lack of consideration is a missed opportunity. However, Ireland's Climate Action Plan 2021 is consistent with both similar plans from the Netherlands and the United Kingdom where water related terms are also seldom mentioned.

A traffic light approach was applied to all 493 actions listed in the Climate Action Plan 2021 to highlight the importance of water quantity in the Plan. Three categories were selected based on the action's described and these are:

- Water Quantity is mentioned or are strongly reliant on water quantity (Mentions WQ)
- Water Quantity needs to be discussed (WQ is important)
- Water Quantity is not relevant (WQ not relevant)

[1] gov.ie - Climate Action Plan 2023 (www.gov.ie)

The full list of actions colour coded are included in the Appendix. Overall, 336 out of 493 Actions (68%) are not related to water quantity and have been excluded from further analysis. Only 36 actions (7%) clearly mention water quantity or are strongly reliant on it. Examples of actions that are colour coded green are shown in Table 3-1.

Table 3-1: Example of Actions that mention water quantity or are strongly reliant on it.

Action 21	Deliver the NPWS/DHLGH Peatlands Restoration Programme for the raised bog habitat within the Special Area of Conservation and Natural Heritage Area networks
Action 157	Introduce pilot biodiversity measures in one of IDA's Business Parks
Action 389	Establish a national soil moisture monitoring network
Action 458	Ensure that six-yearly review of the Flood Risk Management Plans will be informed by the most up-to-date research and projections of climate change on flooding and flood risk; and include other sector-led adaptation measures being implemented under the National Adaptation Framework
Action 475	Review of the Sectoral Adaptation Plan for the Water Quality and Water Services Infrastructure sectors

While some of the above actions clearly mention terms related to water quantity such as soil moisture, flood and Water Services Infrastructure, others are highly reliant on water quantity such as peatlands and biodiversity and therefore coded green.

A larger number of actions (117) do not mention water quantity or terms that should be heavily reliant on water quantity but were deemed that could benefit from including water quantity in the future updates. Table 3-2 gives examples of such actions.

Table 3-2: Example of Actions that do not mention water quantity but would benefit by including water quantity in future updates.

Action 1	Finalise Ireland's long-term climate strategy
Action 13	Deliver the Programme for Government commitment to develop a Green Further Education and Skills Development Plan
Action 38	Deliver the National Climate Change Action and Awareness Programme to support the International Foundation for Environmental Education programmes through Green-Schools, Green-Campus and Young Reporters for the Environment
Action 57	Support the retrofit of public sector buildings
Action 58	Mandate the inclusion of green criteria in all procurements using public funds, introducing requirements on a phased basis and providing appropriate support to procurers
Action 80	Support, monitor and assess Local Authority Climate Action

It is obvious why the inclusion of water quantity into some of the actions in Table 3-2 would have added benefit, for example in Action 1 climate change as already shown will have significant impact on water quantity and this needs to be included in long-term strategies as early as possible. Actions 13 and 38, are related to education and the more aware society and sectors are of the impact of climate change on water quantity the more buy-in will happen to implement adaptation plans. The lack of education in and societal awareness of the impact of climate change was already noted by Augustenborg et al. (2022). They found that the role of climate change in the 2018 droughts was either under or mis-represented. Actions such as 57 and 58, need to include water quantity as a core aspect. To date, all retrofit of building have been focused on energy efficiency; however, our water supply is a limited resource, and the evidence shows that this will become more limited in the future due to climate change, therefore there is a need to plan now to make our buildings more efficient and sustainable in the use of water.

Under the Housing for All Plan and Project Ireland 2040 Strategy projections there will be a need for 300,000 new homes by 2030 (Government of Ireland 2021a) and 500,000 new homes by 2040 (Government of Ireland, 2018, Government of Ireland, 2021b). Cotterill (2021), in a review of domestic water conservation in Ireland, highlighted the need to incorporate water conservation measures into the Government's Housing for All and Project Ireland 2040. This is crucial in the context of increased drought with future climate change, particularly in the south and east of the country.

Flood Risk Management – Climate Change Sectoral Adaptation Plan 2019

The first Flood Risk Management Plan was prepared by the Office of Public Works (OPW) and published in 2015, with the latest update produced in 2019[2]. This plan sets out a long-term goal for adaptation in flood risk management, along with a set of objectives and adaptation actions aimed at achieving those objectives. It states that "*Flooding has the potential to affect all sectors and local authorities, and coordination is critical towards ensuring a coherent and whole of government approach to climate resilience in relation to flooding and flood risk management*". The plan is one of the few sectoral adaptation plans complete and directly related to the impact of climate change and water quantity. The Flood Risk Management Plan has four main aspects:

- Outline the potential impact of climate change on flooding and flood risk management in Ireland
- Identify the objectives for an effective and sustainable approach to climate change adaptation
- Promote a coordinate approach to adaptation
- Recommend any further actions needed to meet adaptation objectives.

The plan highlights the current flood risk management practice, which includes prevention, protection, preparedness, data collection and flood risk assessment. Under these practices climate change is only mentioned in two: under protection, it is noted that increased flood risk due to climate change will be reviewed every six years as required under the EU 'Floods' Directive; while under flood risk assessment, climate change is considered to take the "potential" impacts of climate change into account.

The plan lists the projected changes that it considered based on international and national research:

[2] gov.ie - Climate Change Sectoral Adaptation Plan (www.gov.ie)

- Average temperature to increase by between 0.9 ^{O}C and 1.7 ^{O}C by 2050 across all seasons, with larger increases in the East
- Wetter winters with 20% increase in precipitation
- Change in precipitation patterns remain uncertain
- Drier summer
- Sea level has risen by 3.5 cm per decade since early 1990s

The plan also mentions that at the time of the publication there was "great uncertainty as to how emissions of GHGs will increase or decrease in the future". This goes against the overall consensus at the time that GHG emission would increase without significant action.

These projections are mostly still valid. As previously stated, Nolan and Flanagan (2021) found that by mid-century temperatures would be between 1 ^{O}C and 1.6 ^{O}C warmer, aligning with the range mentioned in the Adaptation Plan. However, Nolan and Flanagan (2021) noted a seasonal variation that was not considered in the Flood Risk Management Adaptation Plan. If we assume the C-C relationship holds for Ireland, the 20% increase in winter precipitation may underestimate the amount by 10% (20% vs 22.5%) by mid-century and by over 100% by the end of the century.

Looking at how the adaptation plans aim to deal with climate change under the different management practices varies greatly. Under prevention, the plan highlights the guidance for zoning is based on existing risk but the guidelines to include climate change are included in the "Guidelines for the Planning System and Flood Risk Management". This guideline was published in 2009 and refers to the OPW for guidance on appropriate allowance for climate change. These allowances are shown in Table 3-3, and uses two scenarios, a mid-range future scenario (MRFS) and a high-end future scenario (HEFS) to give deterministic allowances to account for climate change. These scenarios were developed over 10 years ago and do not include the latest projections or account for spatial variations or any potential impact of catchment size.

Table 3-3: Allowances in Extreme Rainfall Depths, Peak Flood Flows and Mean Sea Level Rise for the Mid-Range Future Scenario and the High-End Future Scenario

Parameter	MRFS	HEFS
Extreme Rainfall Depths	+20%	+30%
Peak Flood Flows	+20%	+30%
Mean Sea Level Rise	+ 500 mm	+1000 mm

Under protection, the adaptation plan states that the design and construction of flood relief schemes will include assessment and investment for adaptation to climate change impacts but provides no specific details. The same is true for preparedness where no details are provided. Under data collection and flood risk assessment, it is noted that climate change may result in flooding of the existing hydrometric network and that a change in focus could be required, such as becoming more low flow focused. Under flood risk assessment, the plan highlights that further analysis beyond what is already done may be necessary.

Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan

The Water Quality and Water Service Infrastructure Climate Change Sectoral Adaptation Plan[3] was developed by the Department of Housing, Planning, Community and Local Government in 2021 with input from a range of stakeholders, including other Government Departments, Irish Water, the OPW and An Foram Uisce. This Sectoral Plan is focused on managing the risks from climate change for water quality and for water services infrastructure and describes the key risks and proposes necessary adaptive measures. While the adaptation plan deals with both water quality and Water Service Infrastructure, this research will only focus on the Water Services Infrastructure as this is more closely related to Water Quantity.

For Water services infrastructure several climate pressures were identified:

- High Temperatures, which could result in increased demand
- High Precipitation and increased storminess potentially causing asset flooding and environmental pollution potential
- High Precipitation resulting in a drawdown of reservoirs levels for flood capacity that reduces capacity if the event is over-estimated.
- Low Precipitation: potentially causing reduced water availability
- Increased storminess/ high temperatures / high precipitation could each result in interruptions to supply

Under each of these pressures, the plan clearly highlights the projected climate change values obtained from the literature. For temperature, it noted values very similar to those of Nolan and Flanagan (2021) with a range between 0.5 ^{O}C and 1.7 ^{O}C by mid-century, however, this lower increase is below the lower increase of 1 ^{O}C (Nolan and Flanagan, 2021). However, the plan does highlight that the south and east of the country will warm faster. For precipitation, the plan agrees with the latest projection that less precipitation will occur annually and that the autumn and winters will get wetter. The plan also states that summer precipitation will decrease by 0% to 30% and this aligns well with Nolan and Flanagan (2021). The plan also notes the dry periods may increase by up to 40%, this is lower than the upper limit suggested by Leahy et al. (2021).

In the Water Quality and Water Service Infrastructure Adaptation Plan, for each of the stated pressures the following impacts and consequences were highlighted:

- Impact 1: Water supply faces high demand and drought conditions at the same time. This is because high temperatures lead to an increase in demand and often occur during low precipitation events when water supplies often face drought conditions, therefore increase stress on the supply of potable water.
    - Consequence 1.1: Environmental risk resulting from increased demand for water in drought conditions includes increased risk of pollution (lack of dilution) of water bodies or over-abstraction.
    - Consequence 1.2: Service provision as high temperature impacts the security of supply due to increase demand and less available supply.

[3] Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan. Link: 057df848-7665-4df1-9abf-1a493f1de7f9.pdf (www.gov.ie)

- Impact 2: Flooding of water abstraction, storage, and treatment works. Heavy precipitation and increased storminess will increase the occurrence of flooding (pluvial/fluvial and groundwater).
    - Consequence 2.1: Asset damage.
    - Consequence 2.2: Complex operational requirements resulting in a potential increase in public health risk.
    - Consequence 2.3: Disruption to service provision.
- Impact 3: Drawdown of Reservoirs. Heavy precipitation may result in operators lowering water levels to ensure necessary storage for flood water.
    - Consequence 3.1: Security of supply in the event predicted flood is smaller than expected.
- Impact 4: Inability of reservoirs to refill and groundwater recharge reduction. This is due to low precipitation that usually occurs with high temperature which increases evapotranspiration, resulting in lower river flow than normal. Directly impacting reservoirs and groundwater storage and can last for several seasons/years.
    - Consequence 4.1: Risk to security of supply,
    - Consequence 4.2: Environmental risk due to over-abstraction from private non-monitored wells.

For each of these impacts and their direct consequences several over-arching adaptive measures were proposed in the adaptation plan including:

1. The need for integrated catchment management and water resource planning to ensure the security of supply
2. Monitoring programme and research
3. Suitable water resources planning frameworks (e,g., licensing of abstraction, drought planning and flood risk assessments)
4. Review of assets to identify assets at risk and implement an upgrade programme.

National Water Resources Plan

The National Water Resources Plan[4] was developed by Uisce Éireann (formerly Irish Water) and is a 25-year strategic framework for water supply services. The National Water Resources Plan is the first such plan for Ireland and consists of two parts:

1. The National Framework Plan. This plan presents a uniform, consistent framework for balancing supply and demand and the impact of climate change on both. This will be discussed in more detail below.
2. Regional Water Resources Plans identify the summary of needs across all water supplies and to identify solutions. As there are 535 individual water supplies in Ireland, these were divided into four regions: Northwest, Southwest, Southeast and Eastern and Midlands, and Uisce Éireann are currently preparing Regional Plans for each region. The final plan is published for the Eastern and Midlands region and draft plans are available for the Southwest and Northwest regions.

[4] National Water Resources Plan | Projects | Uisce Éireann (formerly Irish Water)

The Framework Plan

The aim of Uisce Éireann's Framework Plan, as part of the National Water Resources Plan, was to create guidelines, planning parameters and methodologies to help in the development of solutions for the needs of the four different regions. This Framework Plan considered several different aspects to water supply including:

- Public Water Supply and relevant calculations
- Demand for water and approaches to calculate this
- Regulatory and Licensing Constraints
- Leakage

This research addresses how the Framework Plan deals with climate change and drought planning in Ireland. Prior to discussing how climate change and drought are addressed in the National Water Resources Plan, it is important to understand how Uisce Éireann ensures supply in different climatic conditions and under different extreme weather conditions. Irish Water uses four Weather Event Planning Scenarios for their planning, and these are:

- Normal Year Annual Average (NYAA): this is a typical year with average weather conditions throughout the year. This scenario occurs 90% of the time.
- Dry Year Annual Average (DYAA): this is a year with low rainfall.
- Dry Year Critical Period (DYCP): occurs during the summer of a dry year when demand can be higher than normal.
- Winter Critical Period (WCP): occurs due to freezing conditions.

Climate change in the framework plan is based on several publications published prior to 2016 and therefore has not used the most recent research, even taking into account Uisce Éireann's disclaimer that all data was gathered prior to the Covid-19 pandemic. They use a basic three step approach to assess the impact of climate change.

1. Derive monthly flow factors for the 2050 period. These flow factors were derived from nine large catchments across the Republic of Irish, including the Boyne, Suir, Blackwater and Moy, to estimate the percentage change in monthly flow from a 1961-1990 baseline.
2. Apply these factors to daily flow sequences for each source. Using one of the nine locations and the monthly flow factors, a flow duration curve for any location is generated for which yield can be calculated.
3. Use the projected changes to the hydrology to assess the change in yields. First the impact to yield at the 2050s is determined at linearly scaled to get the impact at the 2041 time horizon for the National Water Resources Plan.

The data used to generate the monthly flow factors comes from an EPA Report in 2008 on "Climate change- refining the Impacts for Ireland" and therefore cannot contain the most recent climate projections. This EPA report uses data from the IPCC Assessment Report 4, which is two generations old and uses empirical downscaling of coarse Global Climate Models (GCMs). In contrast, Nolan and Flanagan (2021) use the latest climate projections available for higher spatial resolution Regional Climate Models (RCMs), which are likely to give more accurate results.

For step 2, the most hydrological similar catchment is to be used; however, with only nine large catchments used to derive monthly flow factors, the smaller catchments in the country may not be represented. This has the potential to introduce significant uncertainties in extrapolation data to smaller catchments.

Appendix E of Irish Water's National Water Resources Plan specifically deals with drought planning. The appendix gives a detailed description of drought risk in Ireland and mentions the three most common droughts that Ireland faces:

- Meteorological drought: lack of precipitation, or precipitation deficit.
- Agricultural drought: soil moisture deficit that typically impacts crop growth
- Hydrological drought: reduced river flows or groundwater levels

It is important to note that hydrological drought is the best definition of droughts that can directly be associated with water supply. Whilst the rest of the National Water Resources Plan used water resource zones, the framework for drought is applied uniformly over each of the three Irish Water Operational Regions (North and West, Eastern and Midlands and Southern Regions) which does not align with the four regions of the National Water Resources Plan. The tactical drought management process follows the approach below:

- Define the triggers. Note one the key indicators used is Standardised Precipitation Index which is used to help define Meteorological droughts and not hydrological droughts. However, soil moisture deficit, river flows, reservoir storage and groundwater levels are also used.
- Identify the plausible management options and assign to escalation points
- Monitor current conditions against these escalation points
- Implement actions as drought develops.

The European Commission stated that all Member States are required to set up a Drought Management Plan (DMP) complementary to the River Basin Management Plan under the Water Framework Directive. The Water Forum, in its submissions on the consultations of Uisce Éireann's regional plans, recommended that regional plans should include drought management plans specific to each region. This is essential considering the expected east-to-west variation in future dry and drought periods due to climate change. Uisce Éireann, in their consultation report to the Eastern and Midlands Regional Plan, stated that drought management plans for each water resource zone would be completed for the next iteration of the NWRP.

Key Points

- The Climate Action Plan 2021 under-represents the importance of securing Ireland water quantity to climate change. Only 7% of the listed Actions mention water quantity and an additional 25% of the Actions would benefit from the inclusion of water quantity to secure supply, protect life and property and increase awareness.
- The Sectoral Plans reviewed do not use the most up-to-date climate analysis. For example, Irish Water's Framework Plan uses climate projections based on AR4, which is two generations old.
- The Flood Risk Management plan is one of the few adaptation plans complete and deals with adaptation to the impact of climate change and flood risk. However, it provides no details on how to undertake this despite stating that the design and

construction of flood relief schemes must include the assessment and investment for climate change adaptation.

Policy Recommendations

- There should be more emphasis on water quantity in Ireland's Climate Action Plan. Action 57 for retrofitting public buildings should not only be in the context of energy efficiency, but also in the context of water efficiency due to potential water shortages during future dry or drought events. Action 58, to mandate the inclusion of green criteria in all procurements using public funds, should include criteria for both energy and water efficiency.
- Ireland's Climate Action Plan in its education and public awareness actions (eg. Action 13 and 38) should include water quantity in the discussion. This will help society understand when difficult decisions are made to deal with the potential impacts of more common and extreme droughts and larger flooding events.
- Future revisions of the National Development Plan and Housing for All Plan should consider how water efficiency can be improved and incorporated into new homes and buildings, to reduce the water per capita demand in order to adapt to future drought conditions and subsequent water shortages.
- The Flood Risk Management – Climate Change Sectoral Adaptation Plan 2019 states that the design and construction of flood relief schemes will include assessment and investment for adaptation to climate change impacts but provides no specific details. The same is true for preparedness where no details are provided. This Flood Risk Management Plan should be reviewed and updated to include the latest scientific data on future projections for Ireland and details of assessment and investment requirements.
- The Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan proposed a number of measures related to water quantity; the need for integrated catchment management and water resource planning to ensure the security of supply; Monitoring programme and research; Suitable water resources planning frameworks (e,g licensing of abstraction, drought planning and flood risk assessments); Review of assets to identify assets at risk and implement an upgrade programme. In advance of a review of this Sectoral Climate Adaptation Plan, a review should be undertaken to determine what progress has been made on these measures since the plan was published.
- Drought management plans should be published for every water resource zone, rather than a uniform application over the whole country.
- The Climate Change framework in the Uisce Éireann's National Water Resource Plan needs to be updated to use the latest climate projections and ensure the methodology is applicable that results are valid across the range of catchments in Ireland.
- Uisce Éireann's National Water Resource Plan needs to look at longer time periods. The current 25-year is too short to ensure that any large infrastructure needed can be designed, obtain planning permission, built and commissioned within it's time frame.

4. Review of Irish National Hydrometric Monitoring Stations

Across the island of Ireland, there are seven different authorities who contributed to the operation of the majority of the Irish National Monitoring stations for water levels and discharge. These are, in order of size of active and historical network:

- The EPA – hydrometric data for rivers, lakes, and groundwater
- OPW – hydrometric and flood data for rivers and lakes
- River Agency Northern Ireland – hydrometric data for rivers, lakes, and groundwater in Northern Ireland
- Waterways Ireland – canal level and flow data
- ESB – hydrometric data for hydroelectric power stations
- Marine Institute – marine and tidal level data
- GSI – groundwater levels

Figure 3-1 shows the distribution of historical and active gauges across the different authorities previously mentioned. In addition, there are five smaller organisations (Port Companies and Trinity College Dublin) who in the past operated a number of stations but are now only responsible for one active location. This figure shows that the EPA, OPW, River Agency Northern Ireland and Waterways Ireland currently operate most active stations, where the EPA has the largest collection of historic gauge locations. Since the beginning of recording of hydrometric data in Ireland, there has been 2565 total number of gauges. However, today only 1031 of these are stated as active (coloured brown in Figure 3.1 below).

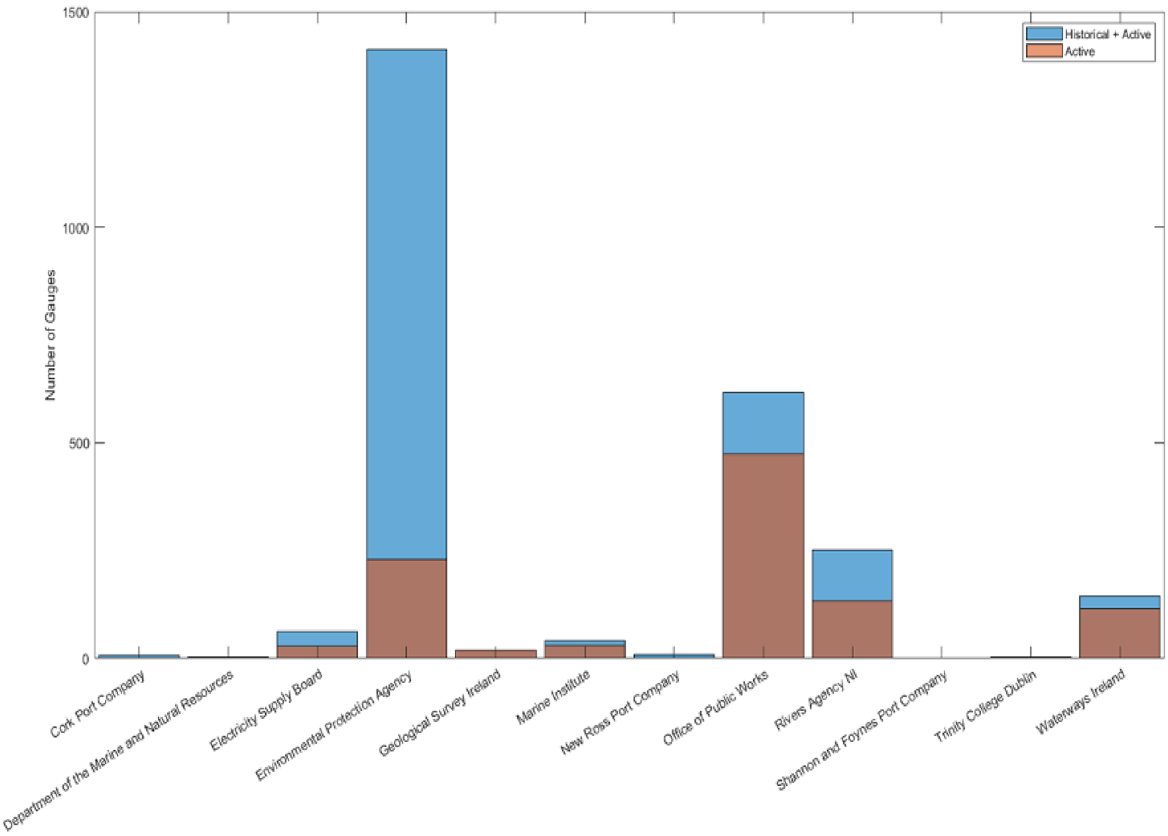

Figure 3-1: Distribution of Historical and Active gauges by responsible Agency.

As shown above there are two authorities responsible for the majority of the gauging locations, the EPA and the OPW. Historically both had different purposes for their gauging locations where the primary focus of the EPA is to provide measurements that are useful for the Water Framework Directive and for the development of water resources, including abstractions for potable water. Therefore, their gauges focused on low and medium flows. On the other hand, the primary purpose of the OPW is flood risk management and their gauges focus on high flows. The location of all active and historic gauges and the body responsible are shown in Figure 3-2.

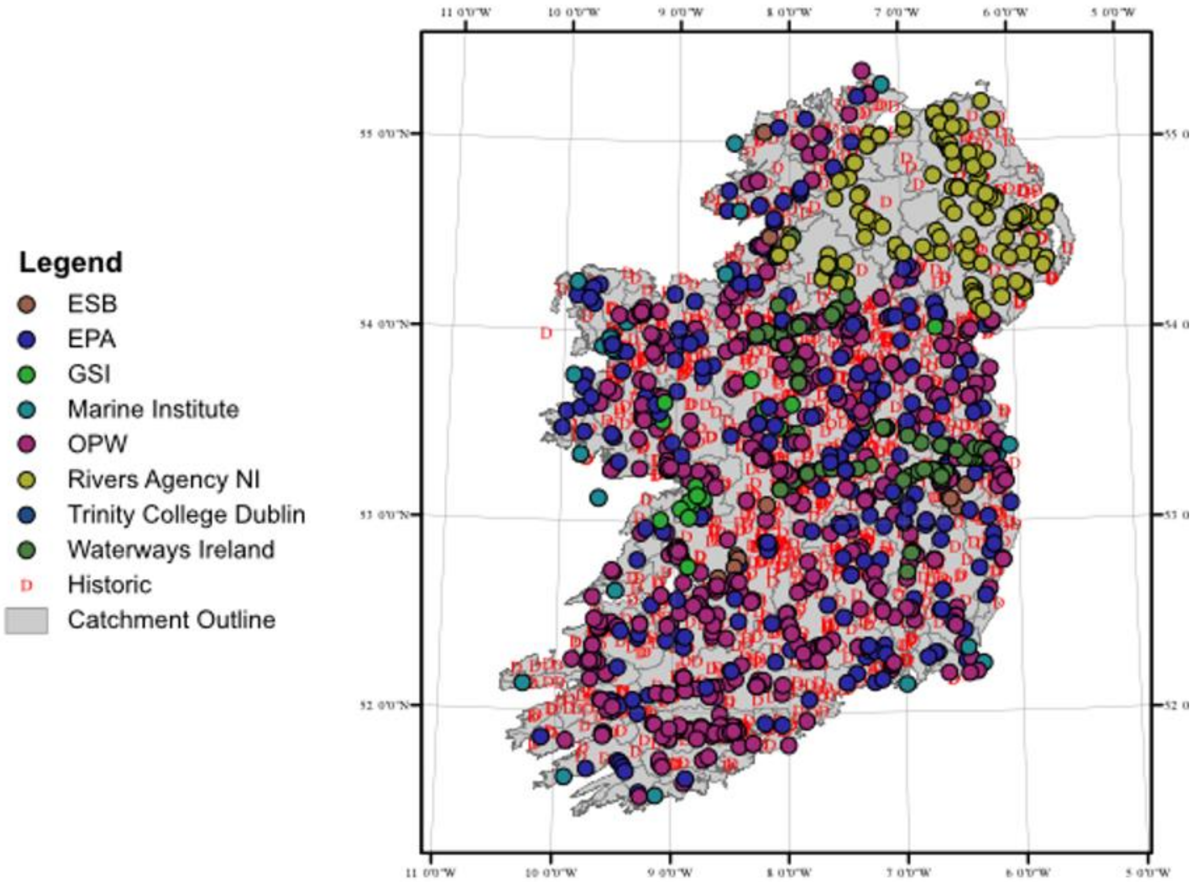

Figure 3-2: Location of Active and Historic Gauges. Agencies responsible for active gauges noted.

As seen in Figure 3-2 there is a good spatial spread of active gauges across the entire island, and these cover a range of catchment size and stream orders. For the Republic of Ireland, the River Network GIS layer (gis.epa.ie) was overlaid with the active stations to determine the percentage of active gauges that correspond to different stream orders. Of the 1031 active stations only 343 gauges were within five metres of an EPA identified steam and the percentage of these to different stream orders are shown in Table 3-1. As expected, there are fewer gauges corresponding to the smallest and largest stream orders as these would be more challenging to gauge/measure due to several reasons such as size, health and safety and flow rates. When catchment size associated with gauging location was investigated (see Table 3-2) there is a clear change in priority over the years, with a reduction in the percentage of smaller catchments (<100 km^2) now having active stations while the percentage of large catchments (>250 km^2) active gauged increasing.

Table 3-1: Percentage of active gauges (within 5 m of a stream) per stream order classification

Stream Order	% of Gauges
1	8.45%
2	8.75%
3	18.37%
4	37.32%
5	20.99%
6	5.25%
7	0.87%

Table 3-2: Number of Gauges (Total, Active and Historic) for a range of catchment size

Catchment Size (km^2)	All	Active	Historic
0 - 25	346 (27%)	69 (11%)	277 (28%)
25 - 100	610 (47%)	165 (26%)	445 (45%)
100 - 250	309 (24%)	160 (25%)	149 (15%)
250 - 500	140 (11%)	88 (14%)	52 (5%)
500 - 1000	83 (6%)	51 (8%)	32 (3%)
1000+	143 (11%)	103 (16%)	40 (4%)

Table 3-3 shows the length of the data record available. As expected, there are very few gauges with record lengths more than 75 years and this is very similar to the global trend. Across all gauges (both active and historic) the average record length is 28.47 years, while the average for open active gauges is 36.1 years. While this average may seem low for active gauges over 30% of gauges have record lengths greater than 50 years.

Table 3-3: Length of record available by Total, Active and Historic Gauge

Record Length (Years)	All	Active	Historic
0 - 10	761 (30%)	217 (21%)	544 (36%)
10 - 25	733 (29%)	272 (26%)	461 (30%)
25 - 50	498 (19%)	225 (22%)	273 (18%)
50 - 75	546 (21%)	300 (29%)	246 (16%)
75 - 100	15 (1%)	15 (1%)	0 (0%)
100+	7 (0%)	2 (0%)	5 (0%)

Another important factor to consider when looking at the gauging network is what type of data is available and if the data is easily accessible. Figure 3-3 shows the data available for active stations. The type of data and the potential usefulness varies significantly. Only 53% of all active gauges provide both estimates of water level and discharge, which means that a current rating curve is available for these locations. 46% of gauging locations provide water level measurements only and no rating curve is available to convert to discharge. However, a number of these would be coastal areas where discharge cannot be accurately estimated using a rating curve. The remaining five percent of gauges provide either water levels and some historic flow estimate or spot flow measurements. This means for the former a rating curve did exist but is no longer valid.

The EPA and OPW operate websites where hydrometric data can be accessed and downloaded. The EPA's website is called hydronet (https://epawebapp.epa.ie/hydronet/) and the OPW's website is called Hydro-data (https://waterlevel.ie/hydro-data/). However, not all the data for the active stations is readily available. For the EPA gauging stations only 93% and 74% of their water level and discharge data, respectively, is available. The percentages are lower for the OPW, with 85% and 84% of water level and discharge data available. However, the OPW operates 475 gauging locations compared to 226 locations operated by the EPA.

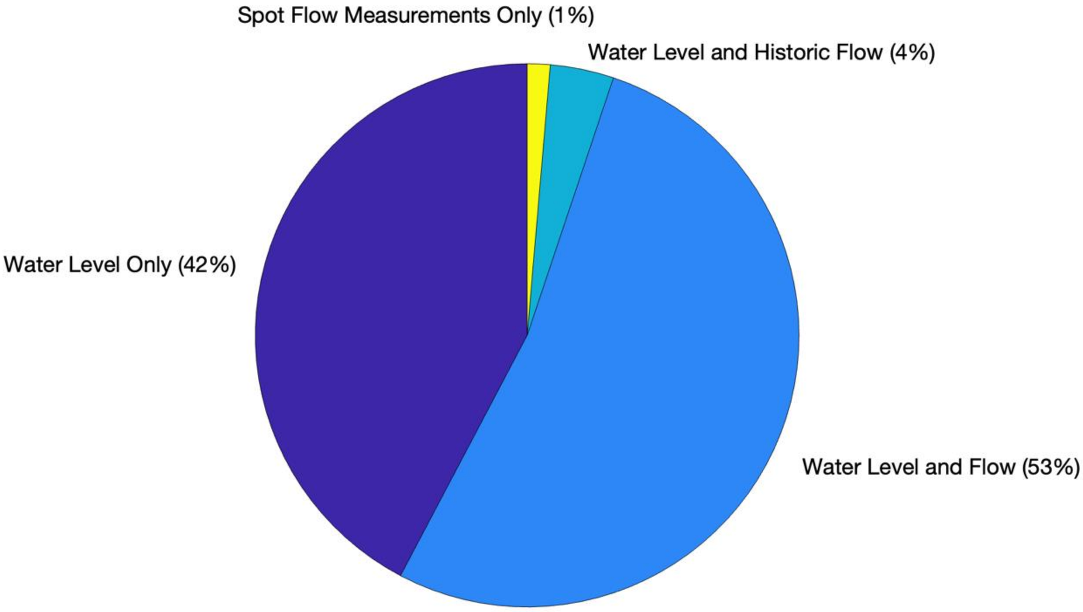

Figure 3-3: Measurements available at Active gauges.

Whilst in the past, the different organisations measuring river discharge or water level worked separately, they have started to coordinate their actions under the National Hydrometric Working Group (Quinlan et al., 2022) and a national register is maintained by the EPA. Under this working group, gauging stations are classified based on importance and these classifications are:

- Strategic: These are permanent stations that help understand the hydrology of Ireland and account for approximately 38% of all gauges.
- Operational: Long-term stations provide data for ongoing use such as flows at wastewater treatment plans and account for over 60% of gauges. Their record lengths are generally less than 10 years.

- Project: Temporary stations installed for a specific use and generally have short record lengths.

Key Points

- Seven different organisations are responsible for collecting water level and flow across the Ireland of Ireland. The OPW, EPA and River Agency NI are the three largest.
- Currently there are 1031 active stations across. These have a good spatial distribution across the island. However, the majority of these are not on the largest or smallest rivers.
- Record length of the active stations show significant variations with only 17 stations with records greater than 75 years and only ~30% of the active stations have record lengths greater than 50 years. This is a significant issue for modelling droughts where longer term records are critical. This was also highlighted in Uisce Éireann's National Water Resource Plan.
- Ireland currently has a National Hydrometric Working Group that is led by the EPA with the objective to coordinate the actions of organisation monitoring river discharge or water level. This Working Group determines if stations should close or if new ones are needed.

Policy Recommendations

- The National Hydrometric Working Group needs to ensure that the hydrometric network is sufficient to meet the demands of its users. This is critical to ensure longevity in monitoring to enable accurate characterisation of both flood and drought events.

5. Change in Water Quantity across Irish Catchments

In the section we present the work done to quantify the change in water balance due to climate change for all river catchments in the all-Ireland catchment shapefile from the Irish EPA. We assume that changes in discharge are a valid proxy for changes in water balance. The "Hydrology-related climate impact indicators from 1980 to 2100 derived from bias adjusted European climate projection" was used to generate the water balance presented in the figures below. This dataset is available to download from https://cds.climate.copernicus.eu/. From this dataset, the gridded hydrological model showing relative mean runoff from the reference period for three RCPs (2.6, 4.5 and 8.5) was chosen and the two hydrological models used were:

- E-HYPEgrid (Donnelly et al., 2016)
- VIC-WUR (Liang *et al.*, 1994)

This dataset has a 5 km spatial resolution, and from this the average mean runoff of both models for each catchment was determined.

Two of the three different RCPs (4.5 and 8.5) where used for the different reference periods available (listed below) were used to give the best overall picture of what is to be expected to happen. RCP 2.6 was ignored as this scenario is no longer feasible due to lack of action by Governments and Industry to reduce GHGs.

- Period 1: 2011- 2040 (denoted as _2011 below)
- Period 2: 2041- 2070 (denoted as _2041 below)
- Period 3: 2071- 2100 (denoted as _2071 below)

Table 4-1 gives the overall summary of the expected relative change in mean runoff from the reference period 1970-2010 across all catchments. There is a lot of variation across the different periods and RCPs but no matter which RCP is chosen, it is clear that there will be catchments in Ireland experiencing significantly reduced mean runoff in the future with maximum decreases in mean discharge expected to be nearly 30% under RCP 8.5 by the end of the century. This table also highlights that some catchments will see an increase in annual mean runoff; however, from the figures, these are small catchments along the West Coast of Ireland.

Table 4-1: Summary Statistics for RCP 4.5 and 8.5 and time-periods (% change)

	RCP45_2011	RCP45_2041	RCP45_2071	RCP85_2011	RCP85_2041	RCP85_2071
Maximum Decrease	-11.09	-14.09	-10.29	-10.16	-18.57	-28.40
Mean	-0.52	-4.22	-0.23	-0.87	-9.10	-10.28
Maximum Increase	6.77	2.99	10.84	5.69	-1.02	3.99

Changes between 2011-2040 and baseline period 1980-2010.

Figures 4-1 and 4-2 shows the percentage change in annual average discharge across Ireland for the time period 2011-2040 compared to the reference time period. There is a clear pattern across the country with the East and South-East experiencing the largest decreases in discharge. This will have significant impact on agriculture and the supply of potable water. Along the Atlantic seaboard, many catchments show a very small increase in annual average discharge. However, the impact of RCP is clearly visible with RCP 8.5 showing an overall drier Ireland by 2040.

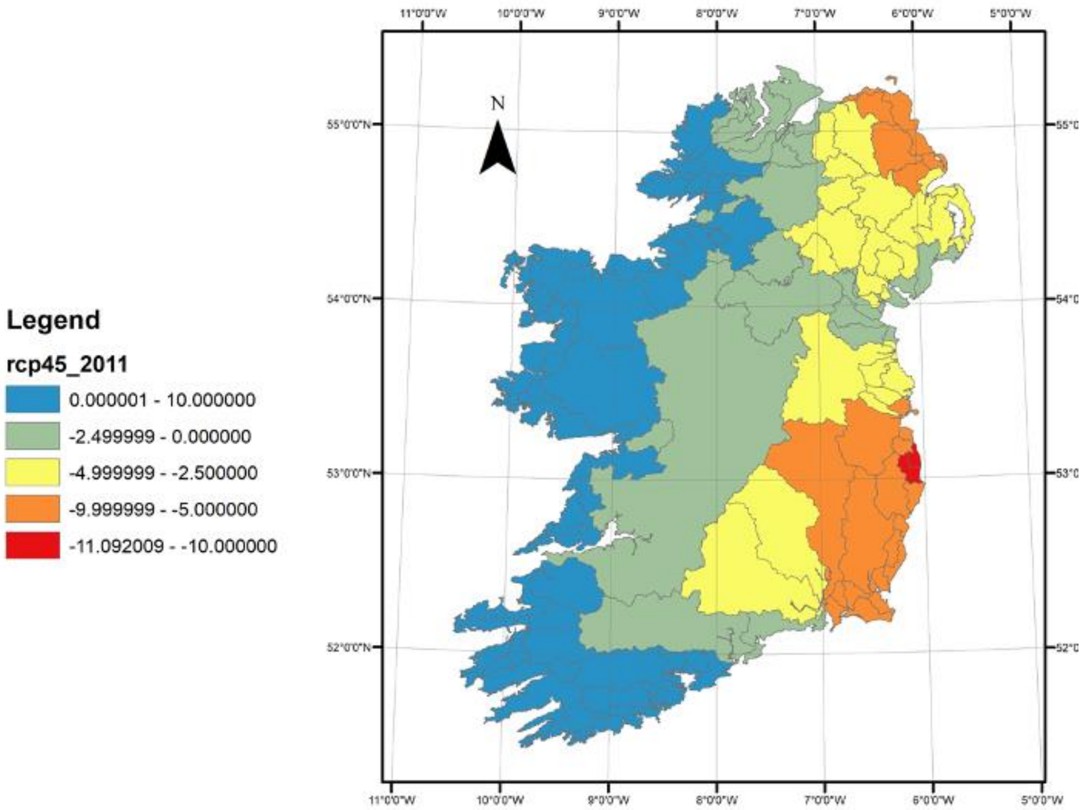

Figure 4-1: Percentage Change in Annual Average Discharge by Catchment for RCP 4.5 and time-period 2011 -2040 compared to baseline 1980-2010.

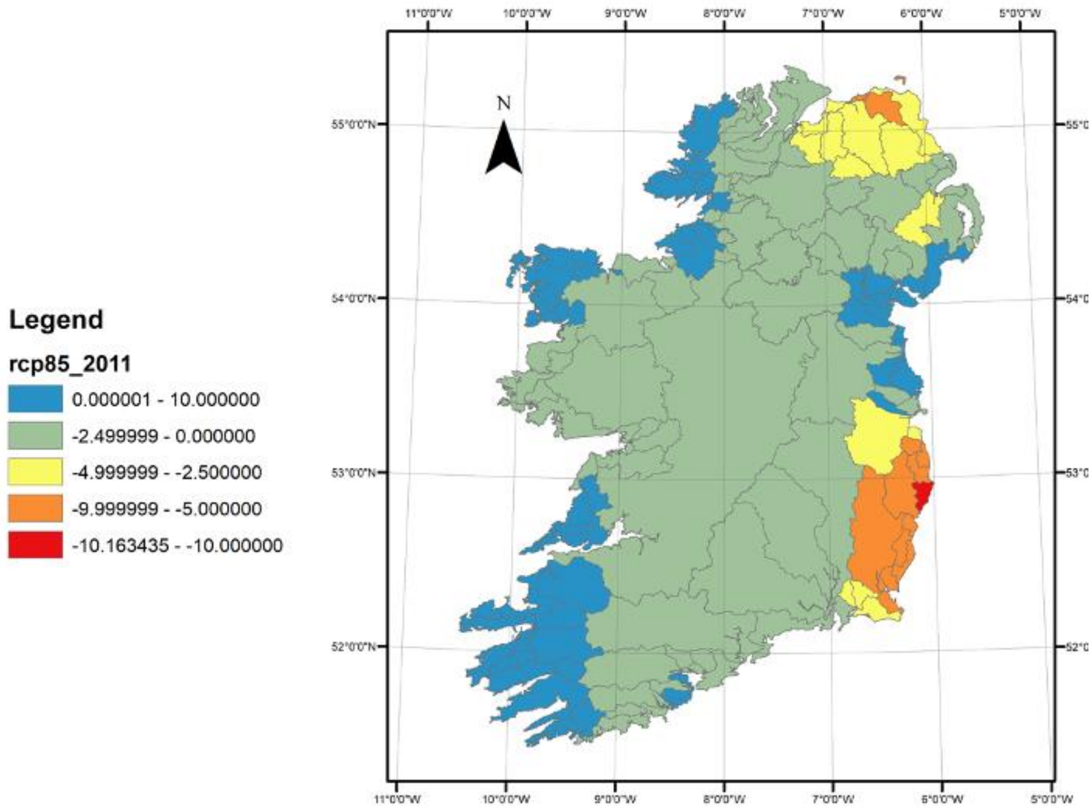

Figure 4-2: Percentage Change in Annual Average Discharge by Catchment for RCP 8.5 and time-period 2011 -2040 compared to baseline 1980-2010.

Changes between 2041-2070 and baseline period 1980-2010.

Figure 4-3 and Figure 4-4 show the change in annual average discharge for the mid-century period (2041-2070). It is clear that Ireland will be a drier with all catchments showing deceases in annual average discharge under RCP 8.5 with the majority of the country expected to see river discharge reduced by 10%. This will have significant impact on the agricultural sector and on all surface water bodies. A similar but less extreme pattern is visible under RCP 4.5 which shows a small number of catchments staying the same or getting slightly wetter under RCP 8.5. Again, no matter which RCP, the East and South-East will be the most severely impacted.

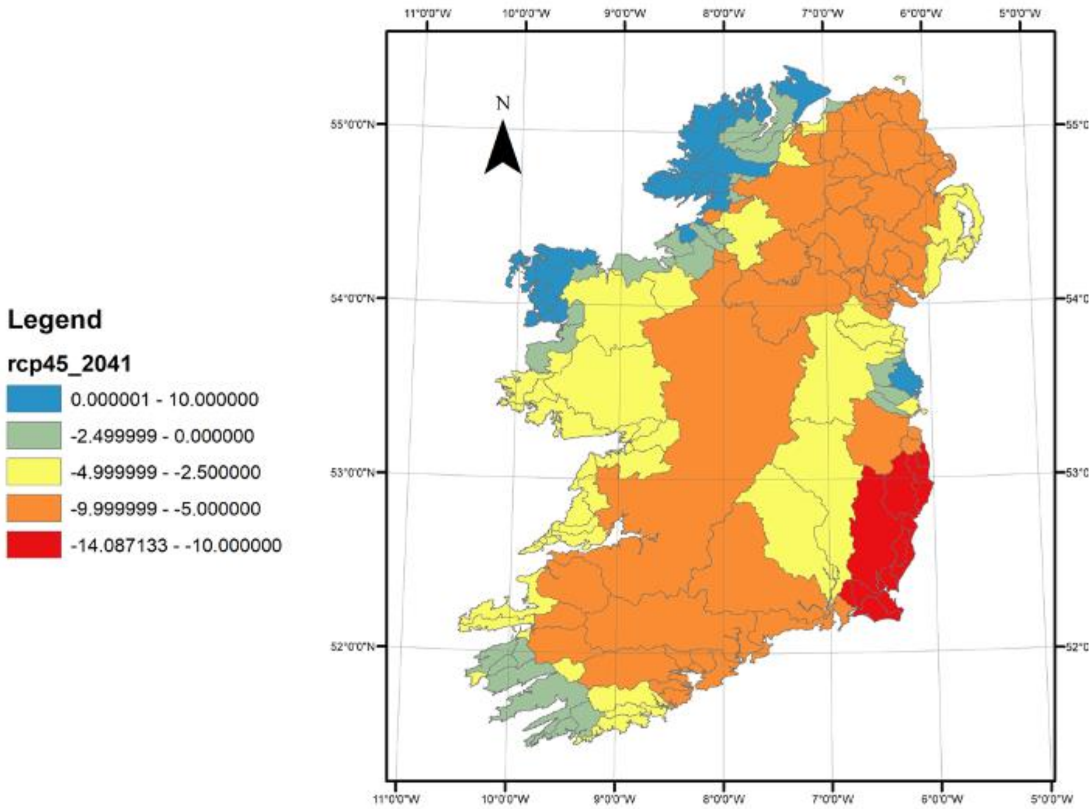

Figure 4-3: Percentage Change in Annual Average Discharge by Catchment for RCP 4.5 and time-period 2041 -2070 compared to baseline 1980-2010.

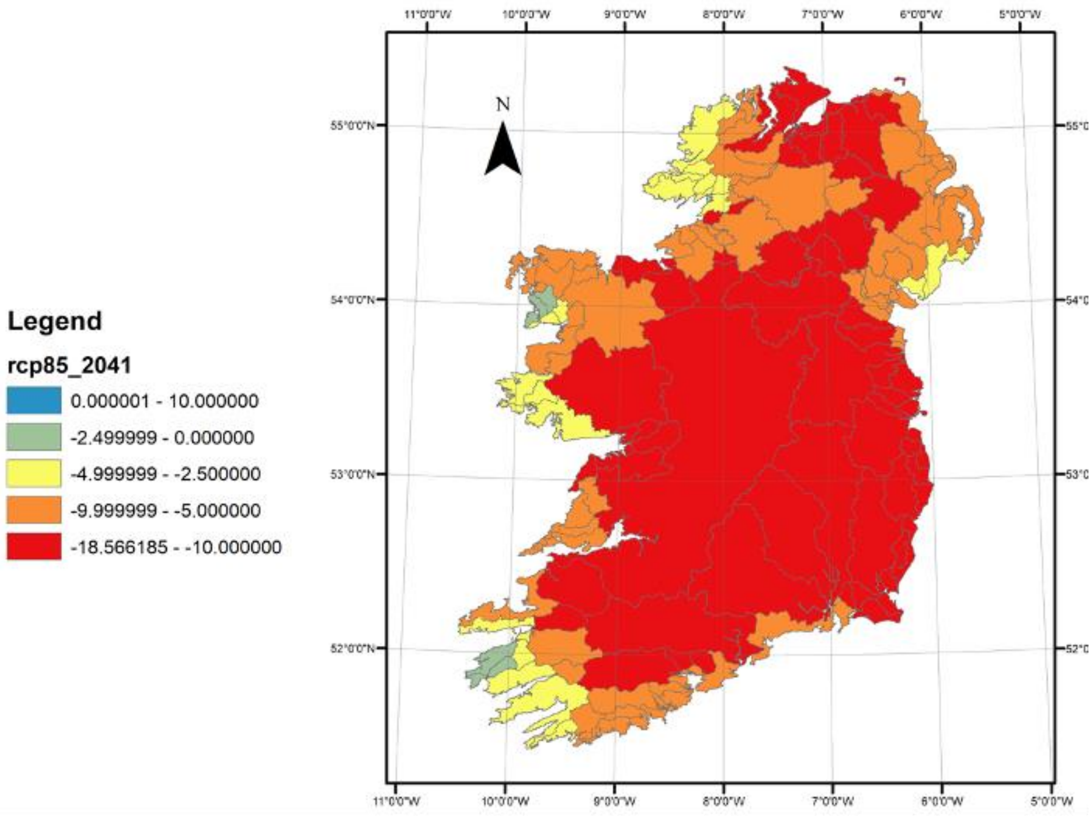

Figure 4-4: Percentage Change in Annual Average Discharge by Catchment for RCP 8.5 and time-period 2041 -2070 compared to baseline 1980-2010.

Changes between 2071-2100 and baseline period 1980-2010.

The following two figures (Figure 4-5 and 4-6) highlight the possible changes in annual average discharge by the end of the century. Again, the East, South-East and North-East will be significantly impacted with a decrease of more than 5% expected. The impact of RCPs and the different GHGs emission pathways are also clearly visible. RCP 4.5 projects GHGs to peak by 2050 and then level off, while RCP 8.5 projects them to continue to rise. Despite the diverging GHGs pathways, under both RCPs most of the country will be drier. Under RCP 8.5 some catchments will experience reduction in annual average discharge in excess of 20%.

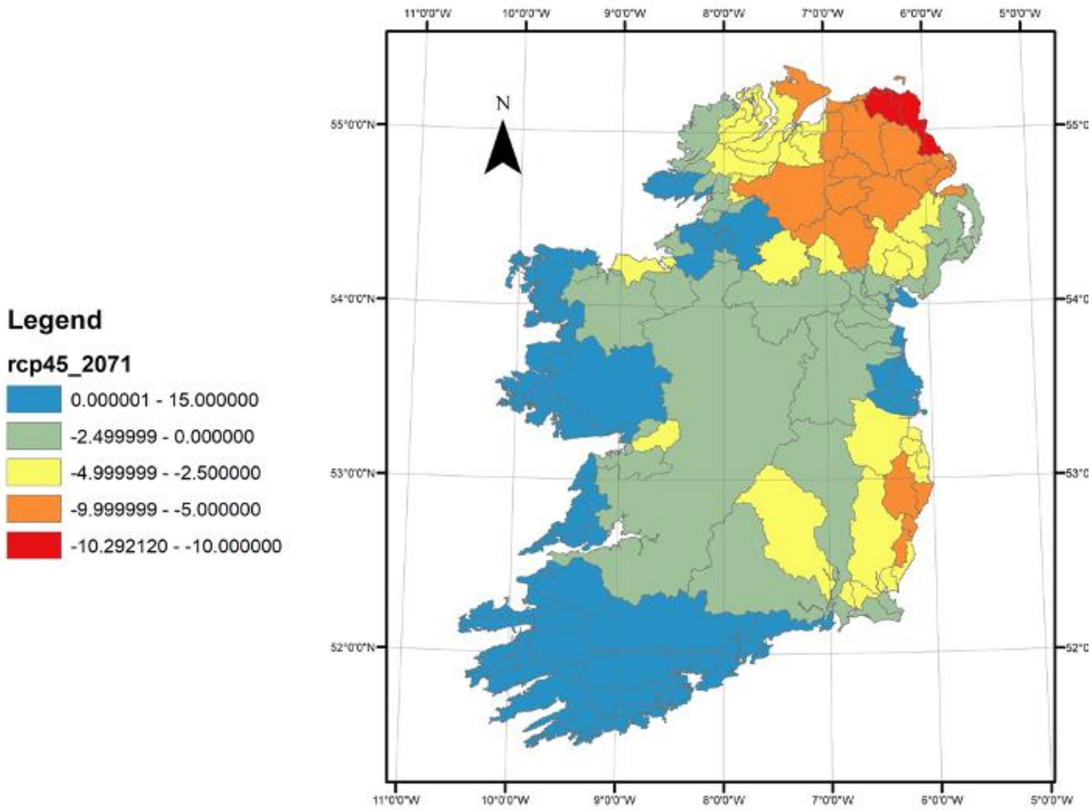

Figure 4-5: Percentage Change in Annual Average Discharge by Catchment for RCP 4.5 and time-period 2071 -2100 compared to baseline 1980-2010.

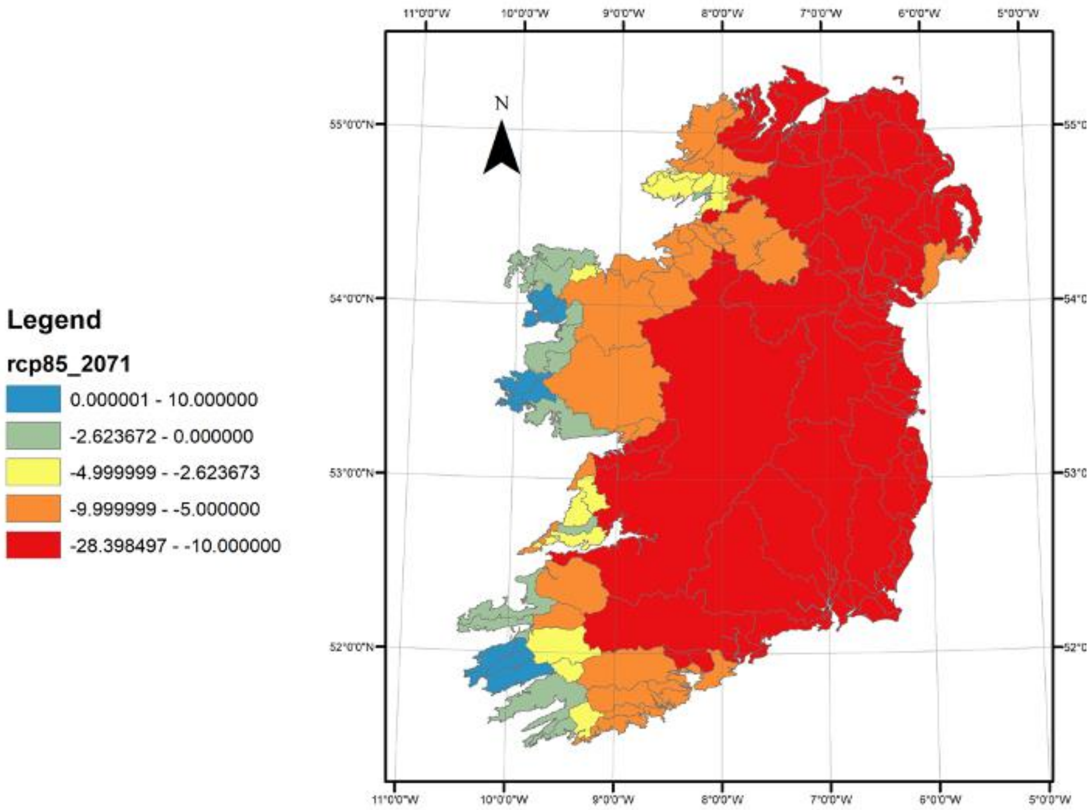

Figure 4-6: Percentage Change in Annual Average Discharge by Catchment for RCP 8.5 and time-period 2071 -2100 compared to baseline 1980-2010.

Key Points

- Regardless of which RCP considered, most of Ireland will be drier in the future. Under RCP 4.5, while on average Ireland will only be slightly drier, some catchments will experience in excess of 10% reductions in annual average discharge. This has the potential to occur by 2040. Under RCP 8.5, Ireland gets significantly drier in the future, while in the 2011-2040 scenario the average reduction in annual average discharge is only ~1%, but by the end of the century this rises to ~10%. There will be significant region to region and even catchment to catchment variations in annual average discharge. All results indicate that the East and South-East will be more heavily impacted than elsewhere.
- Under RCP 4.5, for both 2011-2040 and 2070-2100 periods, catchments along the west coast (from Donegal to Cork) may experience slightly wetter conditions, with an increase in annual average discharge up to 15%. There are very few wetter catchments, even on the west coast under RCP 8.5.
- The impact of these changes and spatial variations on different sectors are not fully understood. However, these changes will have significant impacts on water supply, agriculture and ecosystems.

Policy Recommendations

- There is a need to undertake catchment specific analysis to fully capture the impact of climate change. This is supported by the finding of Hall and Murphy (2011) who noted the non-uniform nature of climate change impacts and highlighted the need for site specific analysis. Even the regional approach used by Uisce Éireann’s National Water Resource Plan fail to capture the catchment-to-catchment variations which could be significant.

6. Discussion, Conclusions and Policy Recommendations

Discussion and Conclusion

The current state of the art on the impact of climate change on Ireland is very clear and has major implications for water quantity across Ireland. The latest IPCC report clearly states that human activities are the main driver in climate change and that we have already caused global temperatures to increase by 1 ^{O}C since the beginning of the 20th Century. Even if significant mitigation measures were introduced to reduce GHGs emissions, global temperatures will continue to rise until at least mid-century and it is likely that global temperatures could increase by 2 ^{O}C without significant action to reduce emissions. Ireland annual trends will follow the global pattern; however, there will be some significant variations across seasons. Summer and Autumn temperatures will increase faster and could potentially see increases of 3.1 ^{O}C by the end of the century (Fealy et al, 2018), with the South and East of the country warming faster than elsewhere.

As temperatures increase, we will also see increases in extreme events, such as heavy rainfall events, floods, prolonged dry spells and droughts (Pörtner et al., 2022a). In Ireland, it is expected that extended dry periods and droughts will increase in frequency by potentially 48% by mid-century (Leahy et al., 2021). On the other hand, when it rains, those events will become more severe with the number of heavy and very heavy rainfall events increasing by up to 30% along western coastal areas, while precipitation will reduce in the Midlands region.

These changes will have a significant impact on water quantity across the entire island of Ireland. As the projections show that Ireland will experience higher temperatures and less annual precipitation, it is extremely likely that droughts will become more frequent and more extreme. This is of particular concern in the East and South of the country which will experience larger increases in temperature. This compounding impact of higher temperatures and less precipitation will make these events worse. Higher temperatures will increase loss from our water bodies and soil through evapotranspiration, making the event more severe. While less annual precipitation will result in these events lasting longer, as the ground will not receive enough rainfall to exit drought conditions. This combination of conditions has the potential to lead to multi-year droughts being experienced, similar to those already being experienced elsewhere in Europe. The increase in heavy and very heavy rainfall days will not be enough to compensate for the lack of annual precipitation but will lead to a significant increase in flood risk. Research has already shown that climate change will lead to higher flood events occurring (Sarkar Basu et al., 2022) and these heavy and very heavy rainfall days will significantly increase the flood risk in urban areas. Willuweit et al. (2016) has already found that urban runoff in Dublin could increase by 30% in the future due to climate change.

How these changes will impact water supplies across the country is less well known. It is predicted that river flows will experience significant decreases in summer months (Charlton et al., 2006) and this will have negative impacts for water supply as most of our potable water comes from surface water sources. However, every catchment will behave differently and there is a need to analyse each separately (Hall and Murphy, 2011) to fully understand the complexities. This can be seen in Section 5 which shows the changes in annual runoff across all catchments in Ireland. Regardless of which RCP is used, catchments in the Southeast in particular will see large reductions in annual river discharges. However, the majority of catchments across Ireland will see a reduction in river discharge and this is a good indicator that surface water supplies will be put under more pressure. We can infer that groundwater levels will also decrease as they generally correlate with decreases in river discharge. However, groundwater responds slowly to rainfall and there is often a lag (time delay) between river discharges increasing and groundwater levels increasing.

How the Irish Government, state agencies and other organisations are responding to climate change varies. The Irish Government Climate Action Plan deals primarily with how to meet the national goal of net zero GHGs emissions by 2050 and covers a range of sectors. However, water quantity or related terms do not appear to be very relevant in this plan, as related terms are only mentioned 43 times and only 7% of all the actions either mention or are strongly associated with water quantity. It is critical that water quantity is included in conversations about a sustainable economy and future climate change, due to the significance of a resilient water supply to support both population growth and economic sustainability.

Ireland's Climate Action Plan has very similar goals to both the United Kingdom (UK) and the Dutch government. While Ireland wants to be net zero by 2050 at the latest, the UK's Climate Change Act also commits to be net zero by 2050, and the Dutch government wants a 95% reduction from their 1990 level by 2050. In a different approach to Ireland or the Netherlands, the UK's Climate Change Act also created an independent body, the Committee on Climate Change (CCC) to ensure targets are evidence-based and fairly assessed. This act also requires the UK government to undertake a climate change risk assessment (CCRA) every five years and a national adaptation programme (NAP). The UK NAP is very similar to Ireland's Sectoral Adaptation Plans; however, it takes the most important risks identified by the CCRA and developed targeted objectives and policies to address them. The six key areas in the CCRA were:

- Flooding and coastal change risks to communities, businesses, and infrastructure.
- Risks to health, well-being, and productivity from higher temperatures.
- Risks of water deficits in public water supply, and for agriculture, energy generation and industry, with impacts on freshwater ecology.
- Risks to natural capital, including soils, coastal, marine, and freshwater ecosystems, and biodiversity.
- Risks from climate-related impacts on domestic and international food production and trade.
- New and emerging pests and diseases, and non-native species, affecting people, plants, and animals.

Clearly water quantity plays an extremely important role in these key areas.

The Flood Risk Management - Climate Change Sectoral Adaptation Plan 2019, is one of the key sectoral plans dealing with climate change and water quantity. This plan sets out how Ireland will deal with climate change and flood risk and discusses adaptation plans under different management practices. However, the report does not fully reflect the current state of knowledge even at publication. For example, the report states that "great uncertainty as to how emissions of GHGs will increase or decrease in the future" and this goes against the overall consensus at the time that GHGs emission would continue to increase without significant action. The majority of projections presented are in line with those from the latest research, despite some upper limits being slightly lower than expected. While the majority of adaptation plans under the different management practices are justified, it must be highlighted that the OPW suggests using one of two scenarios when considering climate change. These are a mid-range future scenario (MRFS) and a high-end future scenario (HEFS) that apply a uniform deterministic allowance for climate change across the entire country and these allowances have not been updated in over 10 years. It is worth noting, that while the Flood Risk Management Plan assesses prevention, protection, preparedness, data collection and flood risk assessment, there is no similar plan for Drought Risk Management, despite increased drought projected for Ireland with climate change.

The Water Quality and Water Service Infrastructure - Climate Change Sectoral Adaptation Plan and Uisce Éireann’s National Water Resources Plan both look at how to adapt Ireland’s water supplies for climate change. Both plans present the different climate factors that are the biggest risk, and these include high temperature and both high and low precipitation. In the Water Quality and Water Service Infrastructure plan the values of projected change are again mostly in line with those published in the latest research, with the one exception - the frequency of dry periods which was lower than that suggested by Leahy et al. (2021). This plan also highlights the potential consequences of climate change impact on water quantity including how it could result in behavioural change and increase competition for water leading to over-abstraction. This is something that has been experienced due to long lasting droughts in California. The plan also highlights the need for catchment modelling, more monitoring, and more regulation.

The National Water Resource Plan is the 25-year strategic plan for Uisce Éireann and its Framework Plan suggested a consistent set of guidelines and methodologies to ensure that Ireland’s water supplies can meet demand. While the framework plans provide a detail set of guidelines and methodologies there are a number of items that need to be highlighted:

- The weather event planning scenarios only considers four scenarios, and all are single year time frames. The results show that Ireland will experience higher temperatures and less annual precipitation, and this could result in multi-year events and could put Ireland’s water supply under increased stress.
- The methodology for investigating climate change uses data from 2008 to develop monthly flow factors for 2050, which are key to the methodology. This data used GCMs from the IPCC Assessment Report 4, which is now two generations old. Additionally, only nine catchments across Ireland are used to derive monthly flows for 2050. These are all large catchments, and it is questionable if these are hydrologically similar for smaller catchments.
- The framework for droughts divides the country into three Operational Regions and these do not align with the four regions in the National Water Resource Plan.

The need for monitoring Ireland’s river flows was mentioned in the majority of the plans. Ireland currently has 1031 active stations and the majority of these are operated by the OPW, EPA and River Agency Northern Ireland. Of major concern for climate change and water quantity is the shortage of long-term data records, as highlighted in Uisce Éireann’s National Water Resources Plan, which makes drought analysis difficult. Across the active gauges, the average record length is only 36.1 years and 317 out of the 1031 active stations have record lengths greater than 50 years and only two stations have record lengths greater than 100 years. The National Hydrometric Working Group has made progress by coordinating their actions and developing a national register, which is maintained by the EPA.

Policy Recommendations

Water Policy

- Throughout Ireland's Climate Action Plan there is a clear under-representation of the role of water quantity. This should be addressed in future revisions with the emphasis to **include water quantity in Climate Action Planning**. Two clear actions where the inclusion of water quantity would have a significant and positive impact are: Action 57 for retrofitting public buildings to include water efficiency to help mitigate the impacts due to future droughts and potential water shortages; Action 58, to mandate the inclusion of green criteria in all procurements using public funds, should include criteria for both energy and water efficiency.

- Future revisions of the **National Development Plan** and **Housing for All Plan** should consider how **water efficiency** can be improved and **incorporated into new homes and buildings**, to reduce the water per capita demand in order to adapt to future drought conditions and subsequent water shortages.

- Revisions of the **Flood Risk Management Plan** should include the **latest scientific data** on future projections for Ireland and d**etails of assessment and investment requirements**. The current "Flood Risk Management – Climate Change Sectoral Adaptation Plan 2019" uses climate change projection prior to 2011 and suggests a national scaling factor to deal with climate change. This needs to be revised. Additionally, the current plan notes the need to consider adaptation in design and preparedness but provides no details.

Management and Governance

- **National Climate Change Risk Assessment**: While Ireland has a draft National Risk Assessment that covers geopolitical, economic, societal, environmental, and technological risks, it is weak in comparison with the UK's CCRA with regard to climate change and water quantity. The UK's CCRA identifies risks and opportunities across all sectors of life, including water quantity, to help inform adaptation measures and highlight where adaptation measures have not kept pace with the latest climate change projections. The National Risk Assessment should be reviewed and updated to include water related risks, in particular water quantity, that are expected with future climate change.

Water Resource Planning

- The record length of active gauging stations is too short to be able to undertake a detailed drought analysis on many catchments. The average record length is ~37 years and only two stations have records longer than 100 years. In addition, Uisce Éireann's National Water Resources Plan highlights this deficiency and the need for longer records. The **National Hydrometric Working Group** who reviews and makes recommendations on the existing network, are perfectly positioned, to **ensure longevity in monitoring stations** across a range of catchment sizes throughout the country going forward.

- One of the key recommendations of the Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan was the need for i**ntegrated catchment management** and **water resource planning** to ensure the security of supply. As shown in Section 5, the response of catchments to climate change varies significantly from one catchment to the next. In addition, the data used in Section 5 only accounts for changes in meteorological drivers (precipitation and temperature) and ignores the impact of land use change which might occur due to a changing environment which will have implications for the hydrological response of a catchment.

Planning for Extreme Events

- **Drought Management Plans** should be **developed and published for every water resource zone**. The roles and responsibilities of government bodies and agencies who have a role in drought management planning should be publicly available, with a clear timeframe for the completion of the drought management plans.

- **Registry of Extreme Events**: Ireland is a signatory to the UN Sendai Framework for Disaster Risk Reduction in 2015 (Kelman, 2015). One of the priorities is to understand disaster risk and part of this is hazard characterisation. Currently, both the OPW and EPA have databases of historical occurrence of floods and droughts; however, this combined into a single registry, under Met Éireann, including information from other bodies, such as Met Éireann and Uisce Éireann would provide a database of historical and current extreme events. The choice of Met Éireann as the host organisation would be consistent with other countries, where the meteorology services host and compile these registries. These types of registries are critical to understand if extreme events are changing in frequency but also to fully understand the drivers causing them.

- Both the OPW's guidance and Uisce Éireann's methodology for dealing with climate change are simple deterministic approaches and do not use the latest projections. Deterministic approaches cannot capture the full variable in the system that probabilistic approaches can. There is a need for **more advance methodologies** such as using probabilistic approaches **to help address the uncertainties in climate projections**. Additionally, the use of catchment models would significantly help in addressing the spatial variability that exists. Hall and Murphy (2011) have already noted the need for site specific analysis, as they noted all catchments will behave differently to climate change. This is also a recommendation of the Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan which stated the "need for integrated catchment management", i.e. Catchment models.

Risk Communication

- **Education** is key for risk communication. Augustenborg et al. (2022) noted based on the 2018 droughts, that delayed media coverage and poor advice may have hampered water conservation efforts. They also found that the role of climate change in intensifying drought was both under and mis-represented. This hampers any positive behavioural changes that might have occurred. This could be addressed through updates of the Climate Action Plan if water quantity and the sustainable use of water was explicitly mentioned in actions regarding education and awareness, such as in Actions 13 and 38.

References

Augustenborg, C.A., Kelleher, L., O'Neill, E., Cloona, H., 2022. Insights from the 2018 Drought in Ireland's Broadsheet Media. Environmental Communication 16, 445–457.

Bastola, S., Murphy, C., Sweeney, J., 2011. The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios. Science of the Total Environment 409, 5403–5415.

Charlton, R., Fealy, R., Moore, S., Sweeney, J., Murphy, C., 2006. Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques. Climatic change 74, 475–491.

Donnelly, C., Andersson, J.C., Arheimer, B., 2016. Using flow signatures and catchment similarities to evaluate the E-HYPE multi-basin model across Europe. Hydrological Sciences Journal 61, 255–273.

Fealy, R., Bruyére, C., Duffy, C., 2018. Regional climate model simulations for Ireland for the 21st century. Environmental Protection Agency: Johnstown Castle, Ireland 264–268.

Gharbia, S.S., Smullen, T., Gill, L., Johnston, P., Pilla, F., 2018. Spatially distributed potential evapotranspiration modeling and climate projections. Science of The Total Environment 633, 571–592.

Hall, J., Murphy, C., 2011. Robust adaptation assessment–climate change and water supply. International Journal of Climate Change Strategies and Management.

Hall, J., Murphy, C., 2010. Vulnerability analysis of future public water supply under changing climate conditions: A study of the Moy Catchment, Western Ireland. Water Resources Management 24, 3527–3545.

Kelman, I., 2015. Climate change and the Sendai framework for disaster risk reduction. International Journal of Disaster Risk Science 6, 117–127.

Kirkpatrick, J.I.M., Olbert, A.I., 2020. Modelling the effects of climate change on urban coastal-fluvial flooding. Journal of Water and Climate Change 11, 270–288.

Leahy, P., Gonzalez, L.H., Hickey, K., Kiely, G., Allen, M., Nowbakht, P., Pasik, A., n.d. ClimAtt: Tools for Climate Change Attribution of Extreme Weather Events.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research: Atmospheres 99, 14415–14428.

Meresa, H., Donegan, S., Golian, S., Murphy, C., 2022. Simulated changes in seasonal and low flows with climate change for Irish catchments. Water 14, 1556.

Meresa, H., Murphy, C., Fealy, R., Golian, S., 2021. Uncertainties and their interaction in flood hazard assessment with climate change. Hydrology and Earth System Sciences 25, 5237–5257.

Morrissey, P., Nolan, P., McCormack, T., Johnston, P., Naughton, O., Bhatnagar, S., Gill, L., 2021. Impacts of climate change on groundwater flooding and ecohydrology in lowland karst. Hydrology and Earth System Sciences 25, 1923–1941.

Nolan, P., Flanagan, J., 2021. Research 339: High-resolution climate projections for Ireland. A multi-model ensemble approach.

Pörtner, Hans-O, Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R.A., Betts, R., Kerr, R.B., Biesbroek, R., 2022a. Climate change 2022: Impacts, adaptation and vulnerability. IPCC Geneva, Switzerland:

Pörtner, Hans-Otto, Roberts, D.C., Poloczanska, E., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., 2022b. IPCC, 2022: Summary for policymakers.

Quinlan, Conor , Nitsche, J., O’Leary, D., Quinn, R.,, Durkin, P., Bourke, M., 2022. National Hydrometric Monitoring Programme 2022 - 2027. Environmental Protection Agency, Wextford, Ireland.

Sarkar Basu, A., Gill, L.W., Pilla, F., Basu, B., 2022. Assessment of climate change impact on the annual maximum flood in an urban river in Dublin, Ireland. Sustainability 14, 4670.

Willuweit, L., O’Sullivan, J.J., Shahumyan, H., 2016. Simulating the effects of climate change, economic and urban planning scenarios on urban runoff patterns of a metropolitan region. Urban Water Journal 13, 803–818.

Appendix