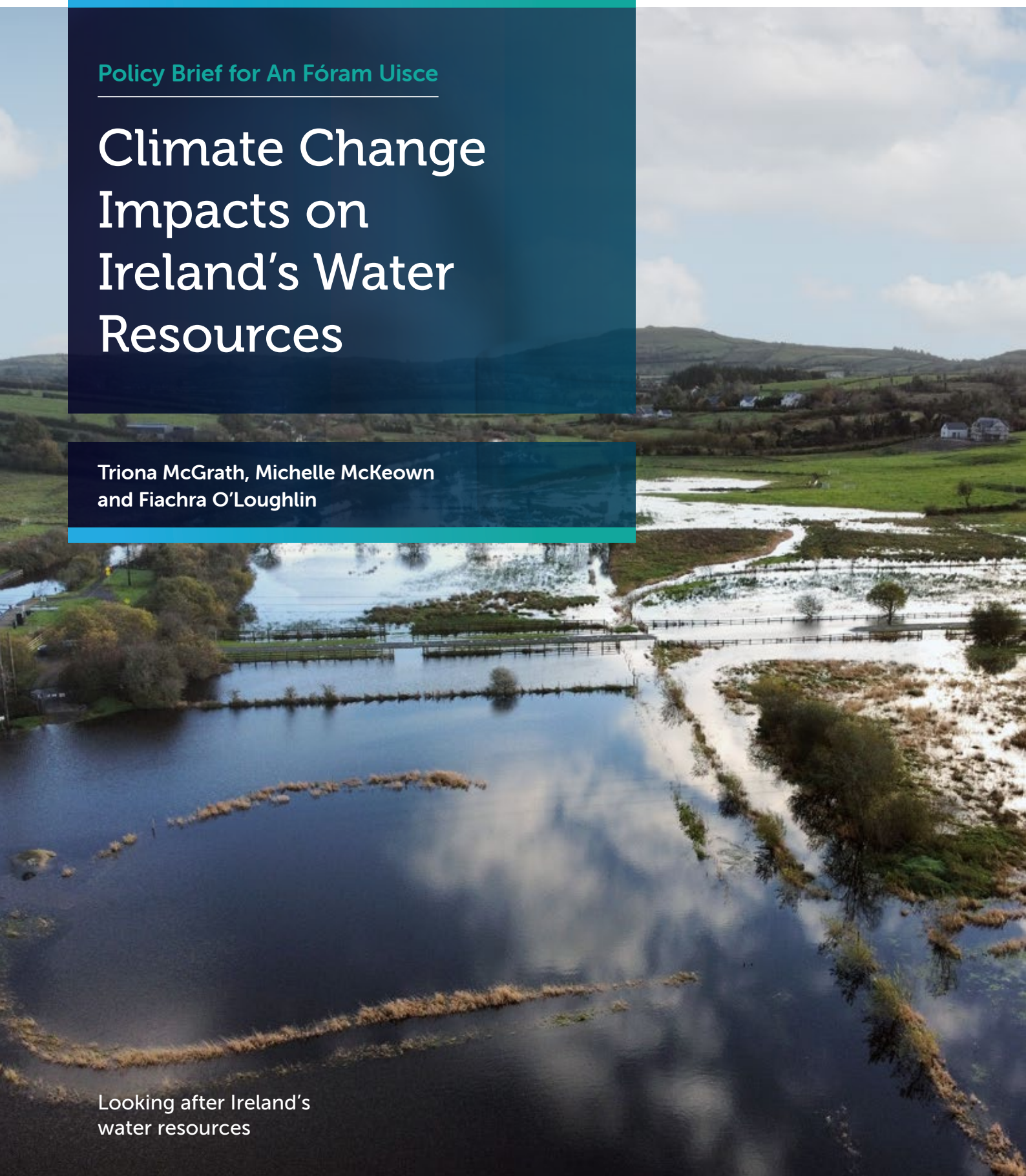


Policy Brief for An Fóram Uisce

Climate Change Impacts on Ireland's Water Resources

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Looking after Ireland's
water resources





Introduction

The global climate change crisis is inextricably linked to water, where climate change is intensifying the water cycle and affecting weather patterns, with more intense rainfall events and flooding in some regions and extended droughts in others¹.

The Climate Status Report for Ireland² indicates changes in seasonality and precipitation patterns, increased incidence of extreme weather events and a gradual continued rise in sea level. Extreme weather events are expected to include more frequent heat waves, extended periods of abnormally low precipitation during summer, increased incidence of heavy precipitation events and flooding, shifts in storm tracks, with significant spatial variation expected across the country³.

Extreme weather events can impact both water availability and water quality. Heavier rainfall and flooding can wash more soil and contaminants from land into our waters, and also overwhelm sewage systems, impacting drinking water, bathing water and aquatic ecosystems. In contrast, extended dry weather or drought conditions can cause water supply issues and can lead to reductions in water levels in rivers, streams and lakes, thereby reducing dilution of pollutants and diminishing water quality. Rising temperatures result in increased stratification in lakes and prevent mixing of oxygen to bottom waters, while also influencing biogeochemical interactions between water and the sediment. Increased temperatures and reduced precipitation may also increase soil organic matter decomposition and therefore the concentration of coloured carbon compounds in catchment waters. This increases the challenges for drinking water treatment and can result in disinfection by-products, such as carcinogenic trihalomethanes.

Over **80%**
of Ireland's public water
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Around **750,000**
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According to the UN, water is the medium through which many of the impacts of the climate crisis are felt by society, therefore water resource management is key for climate change adaptation. National and regional climate policy and planning must take an integrated approach to climate change and water management. Over 80% of Ireland's public water supply comes from surface waters (lakes and rivers), which is used for domestic drinking water supply, wastewater treatment, irrigation, industrial activities, hydropower generation, while also being an important resource for fishing and recreational activities. In addition, around 750,000 people rely on private groundwater sources for daily domestic use. **Water is central to good public health, a functioning environment, a productive economy, and it should therefore be central to climate change action planning.**

In 2022, the Water Forum commissioned two research projects to evaluate if and how Ireland's national policies and climate change adaptation plans address the future risk of climate change to water resources. One project focused on water quantity, *'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'*⁴ which was completed by Dr. Fiachra O'Loughlin, University College Dublin. The second project focussed on water quality, *'Projected climate change in Ireland and associated risk to water quality; policy recommendations for Ireland'*⁵, which was completed by a team of researchers at University College Cork, led by Dr. Michelle McKeown. The following is an overview of key learnings from both research projects, with a summary of policy recommendations which are relevant to national climate action and adaptation planning.

Climate Change Projections for Ireland and Impacts on Water Quantity and Water Quality



Projections: Increased Air and Water Temperature

Increasing Temperatures and Water Quantity

- 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). Temperature projections show a clear west-to-east gradient, with the largest increases in the east³.
- All seasons will experience increases in temperature; however, summer (June, July, August) and autumn (September, October, November) will see the largest increases with 2.8°C increase in summer and 3.1°C warming expected during autumn by the end of the century (2071-2100) under RCP8.5⁶.
- The number of heatwave events is expected to increase between 2041-2060, with largest increases in the southeast of the country⁵.
- Rising air temperatures and heatwaves can increase the temperatures of water bodies (e.g. rivers, lakes). Shallow lakes and wetlands will be particularly susceptible to increasing air and water temperatures due to large surface-to-volume ratios⁷.
- Increasing temperatures will correspond to an increase in evapotranspiration, the amount of water evaporated to the atmosphere from water bodies and plants. The potential evapotranspiration for the Shannon River Basin could be 13.5% larger by 2080 relative to today⁸.

Increasing temperatures may result in INCREASED FREQUENCIES OF CYANOBACTERIAL BLOOMS, some of which produce cyanotoxins, which threaten the safe use of water for drinking and recreational activities

Increasing Temperatures Impacts on Water Quality

- Warmer temperatures can influence the occurrence, stability, reproduction, and mobilisation of pathogens including bacteria, viruses, and parasites in water sources (which differs depending on species). Climate change may therefore alter human exposure to waterborne pathogens through drinking water and recreational waters.
- Increasing temperatures may result in increased frequencies of cyanobacterial blooms¹², some of which produce cyanotoxins, which threaten the safe use of water for drinking and recreational activities. Cyanobacterial blooms can also reduce dissolved oxygen, reduce light penetration, and increase the pH of water. They already cause contamination issues for shellfish in Ireland¹³.
- Warming surface waters increases thermal stratification of water bodies, which prevents the movement of oxygen between the surface and the bottom and can result in oxygen depletion of bottom waters⁹. Furthermore, warming and altered stratification can exacerbate the effects of eutrophication through sediment suspension, with nutrient and metal release from sediments^{10,11}.
- Increased temperatures stimulate microbial activities in organic matter decomposition and thus enhance dissolved organic carbon (DOC) production^{14,15}, which will exacerbate disinfection by-product issues in drinking water, such as the formation of carcinogenic trihalomethanes (THMs).



Bohernabreena reservoir, a drinking water source for County Dublin.



Projections: Extended Periods of Abnormally Low Precipitation (Droughts)

Reduced Precipitation and Water Quantity

- Extended dry periods (of > 5 days with <1 mm of precipitation) will become more common in Ireland, increasing by an average of 16%, with largest increases in these periods during the summer months (21 – 27%)^{5,6,16}.
- There is an increased risk that droughts will become more regular, longer and with potential for multi-year droughts, which is already happening elsewhere in Europe¹⁷.
- There will be large decreases in low flows of streams and rivers in Ireland during summer periods and by the 2080s models project that Q95 flows (lowest 5 percentile flows) will have reduced by approximately 21%¹⁸.

There is an INCREASED RISK THAT DROUGHTS will become more regular, longer and with potential for multi-year droughts

Reduced Precipitation Impacts on Water Quality

- A reduction in flows and levels of rivers and lakes results in less dilution of contaminants present in surface and subsurface waters and could lead to concentrations of pollutants above Environmental Quality Standards.
- Accumulation of nutrients and contaminants in soil during extended dry periods could be released in higher concentrations through subsequent pulse/flooding events.
- Severe degradation (drying) of organic rich soils, i.e. peatlands will cause accelerated peat decomposition, export of dissolved organic carbon and particulate organic matter^{14,15}. Increased dissolved organic carbon will exacerbate disinfection by-product issues in drinking water, such as the formation of carcinogenic trihalomethanes (THMs).



Projections: Increased Frequency of rapid high intensity precipitation and flooding

Increased Flooding and Water Quantity

- Climate models indicate there will be an increase in the frequency and duration of heavy rainfall events in Ireland, particularly during autumn and winter.
- The number of wet days >20mm/day is expected to increase by between 9% (RCP 4.5) and 16% (RCP 8.5), while the number of very wet days >30mm/day is expected to increase by between 21% (RCP 4.5) and 31% (RCP8.5). Largest increases will occur in the north and west coast of Ireland³.
- This change in the number of heavy and very heavy rainfall days will have a direct impact on flows in Irish rivers. Studies show that higher/maximum flows are expected in winter, corresponding to an increased flood risk, where annual maximum flows could increase by between 12% and 16% for 50- and 100- year return periods^{18, 19, 20}.
- Flood levels will increase in lowland karst systems²¹.
- Urban runoff in Dublin could increase by 30% in the winter months²².

Increased Flooding Impacts on Water Quality

- Rapid high intensity precipitation mobilises contaminants, sediments, and waterborne pathogens from land to water or from one water system to another (i.e., stream to coastal system)^{23, 24}.
- Water quality of surface and subsurface water bodies will be affected, particularly groundwater in vulnerable karst regions²⁵.
- High rainfall and flooding can overwhelm sewage systems resulting in stormwater overflows. Wastewater effluent and stormwater overflows released to receiving waters can have high concentrations of pathogens, active pharmaceutical ingredients, household chemicals, heavy metals, hydrocarbons, pesticides and excess nutrients²⁶.
- This can impact the quality of receiving water bodies, drinking water sources, bathing waters and the seafood industry.



Projections: Sea Level Rise

Sea level Rise and Water Quantity

- Global sea levels are expected to increase between 0.43 – 0.84m by the end of the century
- In Ireland, mean sea level trends are in line with global trends²⁷.
- Larger local sea level rise has been observed in Cork and Dublin, with recent rates of relative sea level rise being twice the global average in Dublin^{28, 29}.

Sea Level Rise Impacts on Water Quality

- Saline intrusion in some coastal aquifers and estuaries may affect groundwater drinking water resources by increasing total dissolved solids concentrations, altering the biogeochemistry of the aquifers and increasing corrosion of buried infrastructure, with implications for water treatment³⁰.

Existing Challenges for Ireland

The impacts of climate change will occur in conjunction to an existing adaptation deficit for the sustainable management of Irish water resources.

Water Quality

- The water quality of Ireland's lakes, rivers, estuaries and coastal waters has declined in the last five years (2016-2021) according to the recent EPA report on 'Water Quality in Ireland, 2016-2021'³¹.
- In the latest assessment only 54% of Ireland's water bodies meet the minimum requirement status (good) as set out in the EU Water Framework Directive.

Climate Change is expected to exacerbate existing pressures on water quality, altering the mobility and pathways of pollutants from land into water bodies.

Wastewater

- Twelve urban areas currently fail to meet the EU Waste Water Treatment Standards³², which includes Ringsend in Dublin which serves 42% of Ireland's population, where inadequately treated waste water is being discharged into the environment impacting both public health and ecosystems.
- Stormwater overflows are outlets from collecting systems designed to relieve sewers of excess flows caused by unusually heavy rainfall, where they release excess flow from the sewer directly into local waters. 25% of stormwater overflow outlets assessed in 2020 did not meet the necessary standards, meaning that during storm events untreated sewage is entering surface waters, putting the environment and public health at risk.

Future climate change will exacerbate risks from inadequate wastewater treatment due to increased frequency of flood events and increased pollutant concentrations during low flows.

25%

of stormwater overflow outlets assessed in 2020 did not meet the necessary standards, meaning that during storm events untreated sewage is entering surface waters

Drinking water supply

- Ireland has existing challenges in water supply infrastructure, with 38% of treated drinking water lost through leakage.
- Furthermore, Uisce Éireann have stated that 58% of public water supplies have a supply demand deficit in normal conditions, which increases to 66% during drought.
- The record length of active hydrometric monitoring stations in Ireland varies, with only 17 stations (of 1031) with records greater than 75 years and only ~30% with record lengths greater than 50 years. This provides a significant issue for modelling droughts. Ireland does not yet have any drought management plans developed for its water resource zones.

Increased frequency and magnitude of extended dry/drought conditions will add additional pressure to water availability for sustainable abstraction during summer months.

Drinking water quality

- Ireland has the highest reported trihalomethanes (THM) exceedances in potable water across the European Union¹⁵. THMs are a disinfection by-product of treatment of waters sourced in peatland catchments. In Ireland, 68% of the national population receives drinking water from a peat-fed water supply system, which includes water from the Liffey catchment supplying the Greater Dublin Area.

Increased temperatures and reduced precipitation cause severe degradation (drying) of organic rich soils, i.e., peatlands, resulting in accelerated peat decomposition and export of dissolved organic carbon and particulate organic matter. This will exacerbate disinfection by-product issues in drinking water, such as the formation of carcinogenic THMs, thereby increasing the treatment cost of drinking water and failure to meet EU obligations.

A Review of National Policies with Policy Recommendations for Ireland

Ireland's Climate Action Plan

Ireland's Climate Action Plan is the roadmap for meeting Ireland's 2050 national climate objective, with the overall aim to halve Ireland's greenhouse emission by 2030 and reach net zero by 2050 at the latest.

The impact of climate change on water quantity and on water quality, and the necessity for effective water resource management for climate change adaptation, is notably underrepresented in the Climate Action Plan 2021. This is a significant gap since water is the medium through which many of the impacts of the climate crises will be felt by society.

Recommendations:

There should be better representation of the significance of water quantity and water quality in Ireland's Climate Action Plan.

- Water conservation and water efficiency should be used as tools for both climate change mitigation, where reduced demand requires less energy for treatment and supply, and climate adaptation, to adapt to future droughts and potential water shortages.
- Ireland's Climate Action Plan should include water efficiency targets for future housing and developments to ensure buildings are both energy and water efficient. This should be supported by an ambitious amendment to the Building Regulations to specify total water use per building and maximum ratings for fittings³⁷.
- 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 potential water shortages.
- Actions that address education and awareness in climate change should include education on water as a resource and how water conservation could be used for both climate change mitigation and adaptation.

Water is the medium through which many of the IMPACTS OF THE CLIMATE CRISES will be felt by society

Sectoral Adaptation Plans

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

The Water Quality and Water Service Infrastructure – Climate Change Sectoral Adaptation Plan is one of nine *Climate Change Sectoral Adaptation Plans* in response to statutory requirements of the Climate Act 2015. This plan was prepared by the Department of Housing, Local Government and Heritage and focuses on managing the risks from climate change for water quality and for water services infrastructure.

This plan is comprehensive in its approach and a list of acute priority impacts is presented, which includes impacts from flooding and mobilisation of pollutants, reduced dilution of contaminants at low flow and increased spread and viability of pathogens, such as livestock waste and slurry. However, based on the latest scientific literature review, several discrepancies are still evident amongst other impacts listed in this comprehensive plan.

Recommendations:

The Water Quality and Water Services Climate Change Sectoral Adaptation Plan should be revised and include the following recommendations from Taylor et al., (2023)⁵:

- Increased lake water temperatures will alter thermal stratification patterns (lake mixing) resulting in major physical, chemical, and ecological effects in freshwater lakes. This can impact water quality through an acceleration of lake deoxygenation with subsequent effects on nutrient mineralisation and phosphorus release from hypoxic and/or anoxic lake sediments.
- Increasing temperatures and stratification will exacerbate effects of eutrophication and increased frequencies of cyanobacterial blooms.
- Increased export of dissolved organic carbon and particulate organic matter from organic rich soils and implications for both the ecology of receiving waters and for the quality and treatment costs of water used for human consumption.
- Increased contamination and mobilisation of nutrients associated with high-intensity precipitation events and flooding for groundwater in karst regions.
- Atmospheric wet deposition of nutrients, particularly nitrogen and ammonium should be included as a pollutant source in surface waters.

The Flood Risk Management Climate Change Sectoral Adaptation Plan

The Flood Risk Management – Climate Change Sectoral Adaptation Plan 2019, prepared by the Office of Public Works (OPW), 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.

Recommendations:

The Flood Risk Management Climate Change Sectoral Adaptation Plan should be revised to include the latest climate projections for Ireland that accounts for the spatial variation in precipitation expected in Ireland. The next iteration of the plan should aim to use the catchment as the management unit, where possible, building on catchment management plans proposed for the 3rd River Basin Management Plan.

Drought management and supporting policies and legislation in the UK and elsewhere in Europe are considerably MORE ADVANCED THAN IN IRELAND at present

Drought Management Planning

The European Commission stated that all Member States should develop Drought Management Plans complementary to the River Basin Management Plan under the Water Framework Directive³³, which has still not been delivered for Ireland.

Drought management and supporting policies and legislation in the UK and elsewhere in Europe are considerably more advanced than in Ireland at present; for example, water companies in England and Wales are obliged to produce a drought management plan every five years³⁴, while England have prepared a report, 'Preparing for a drier future; England's water infrastructure needs' which outlines how England will address water supply challenges and deliver the appropriate level of resilience for the long term.

Recommendations:

Drought Management Plans should be developed at catchment scale, where possible, again to account for the spatial variation in precipitation expected across Ireland. These drought management plans, along with 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 development and implementation of the drought management plans.

Drought management plans would also help inform future planning decisions around water efficiency standards in new housing developments.



Lough Anna, Co. Donegal which provides the drinking water supply for Glenties and Ardara.

Governance and Policy Coherence

There should be a commitment within future iterations of the Climate Action Plan for greater policy coherence and alignment of climate, water, and nature objectives, which would support greater integration of resources with optimum environmental benefits.

In 2020 the Water Forum adopted the Framework for Integrated Land and Landscape Management (FILLM)³⁵ as a framework for environmental management to address the interconnectedness of natural systems. This integrated approach would facilitate the identification of co-benefits of various measures to ensure optimum results for efforts and resources used, while also supporting decision making around trade-offs, where required. FILLM states that Programmes of Measures for water resources, biodiversity and climate change adaptation and mitigation should be developed and implemented in an integrated manner.

There should be an increase in transparency in roles and responsibilities in climate adaptation among government bodies, state agencies, non-government organisations and any other relevant stakeholders, to ensure accountability for action for climate adaptation measures and sustainable water resource management. Furthermore, there should be greater communication and synergies between government bodies, stakeholders and higher education institutes to ensure climate adaptation planning and water resource management is supported by the latest research, to identify research gaps in relation to climate change impacts on Ireland's water resources.



Education and Awareness

There is currently a lack of knowledge of the potential impacts of climate change on water resources in Ireland and subsequent implications for public health and the environment.

There is also a lack of awareness of existing challenges to secure high quality drinking water for a growing population, which will be further stressed with future climate change. Augustenborg et al. (2022)³⁶ found that the role of climate change in intensifying drought was both under and misrepresented during the 2018 drought in Ireland, and the delayed media coverage may have hampered water conservation efforts.

Education and awareness play a crucial role in addressing water-climate-related issues in Ireland.

Recommendations: Promoting awareness in this area can be achieved by:

- Public awareness campaigns (television, radio, social and print media) should be launched targeting the general public about water and climate related issues. These campaigns should highlight success stories and inspire individual action.
- Education should focus on the bottom up understanding of water, from the processes that underpin treatment and supply, to the energy and resources required to produce drinking water³⁷.
- Water-climate topics should be incorporated into school curricula at all levels to raise awareness among students and promote a deeper understanding of water-related challenges and solutions.

- Community engagement through workshops, seminars, and interactive sessions to raise awareness and provide information on sustainable water management practices should be included in Local Authority Climate Action Plans. Encourage community members to participate in conservation initiatives and provide resources or incentives to support their efforts.
- Utilise technology to enhance education and awareness, similar to biodiversity campaigns like City Nature Challenge, where interactive mobile applications and online platforms are used to engage the public in entertaining and educational activities. This approach can attract interest in younger generations.
- Aligning communication action for climate, water and biodiversity would also benefit communities, making environmental management more understandable, less fragmented and thus more achievable. Communities should be informed of the different co-benefits that may exist from the measures or actions they are being asked to implement.

PUBLIC AWARENESS CAMPAIGNS
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Further Research

Funding should be allocated and research calls expedited to address strategic priority relevant to increasing knowledge on climate change impacts on both water quantity and water quality in Ireland. Research should include:

- The exacerbated effects of eutrophication and the presence of cyanobacterial blooms relating to warmer temperatures and modified precipitation.
- The anticipated impacts of dissolved organic carbon (DOC) from organic soils and peatlands due to climate change on water bodies and resulting contaminant mitigation in drinking water treatment. DOC export is currently not regulated in Irish surface waters and will likely pose a significant issue to the functioning and cost of water treatment processes for human consumption.
- The influence of atmospheric wet deposition of nutrients e.g., nitrogen and ammonium and subsequent enrichment should be explored.

- Groundwater quality (monitoring) in karst regions, regional/local sea level rise monitoring and enhanced understanding of storm activity in Ireland, along with the extent of saline intrusion in vulnerable groundwater drinking water sources.
- Marine and freshwater acidification impacts on water quality and aquatic ecosystems.

Funding should be allocated and research calls expedited to address strategic priority relevant to INCREASING KNOWLEDGE on climate change impacts on water resources





References

- United Nations (2019). Climate Change and Water UN-Water Policy Brief. Available at [UN_Water_PolicyBrief_ClimateChange_Water.pdf](https://www.unwater.org/publications/research/climate-change-water) (unwater.org)
- Cámaro García W, Dwyer N (2021). Research 386: The Status of Ireland's Climate, 2020. Environmental Protection Agency. Wexford. ISBN: 978-1-80009-009-5. Available at: www.epa.ie/publications/research/climate-change/research-386-the-status-of-irelands-climate-2020.php
- Nolan, P., Flanagan, J. (2020). Report 339: High-resolution Climate Projections for Ireland – A Multi-model ensemble approach. Environmental Protection Agency. Wexford. Available at: www.epa.ie/publications/research/climate-change/Research_Report_339_Part1.pdf
- O'Loughlin, F., Mozafari, B., (2023). 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. Research Commissioned by the Water Forum. Available at: www.thewaterforum.ie/app/uploads/2023/06/Projected-climate-change-in-Ireland-and-associated-risk-to-water-quantity_final.pdf
- Taylor, K., Jansen, M., O'Dwyer, J., Sullivan, T., Weatherill, J., Harrison, S., Banning, A. and McKeown, M. (2023). Addressing Projected Climate Change Risk to Water Quality in Ireland. Research Commissioned by the Water Forum. Available at: www.thewaterforum.ie/app/uploads/2023/06/Research-Report-Climate-Change-Water-Quality-McKeown.pdf
- Fealy, R., Bruyère, C. and Duffy, C. (2018) 'Regional climate model simulations for Ireland for the 21st century', Environmental Protection Agency: Johnstown Castle, Ireland, pp. 264–268.
- Feuchtmayr H., Moran, R., Hatton, K., Connor, L., Heyes, T., Moss, B., Harvey, I., Atkinson, D. (2009) Global warming and eutrophication: effects on water chemistry and autotrophic communities in experimental hypertrophic shallow lake mesocosms. *Journal of Applied Ecology* 46, 713–723. DOI: [Global warming and eutrophication: effects on water chemistry and autotrophic communities in experimental hypertrophic shallow lake mesocosms - Feuchtmayr - 2009 - Journal of Applied Ecology - Wiley Online Library](https://doi.org/10.1111/j.1365-2745.2009.01608.x)
- Gharbia, S.; Smullen, T., Gill, T., Johnston, P., Pilla, F. (2018) 'Spatially distributed potential evapotranspiration modelling and climate projections', *Science of The Total Environment*, 633, pp. 571–592. DOI: [www.doi.org/10.1016/j.scitotenv.2018.03.208](https://doi.org/10.1016/j.scitotenv.2018.03.208)
- Jane, S.F., Hansen, G.J.A., Kraemer, B.M. et al. (2021). Widespread deoxygenation of temperate lakes. *Nature* 594, 66–70. [www.doi.org/10.1038/s41586-021-03550-y](https://doi.org/10.1038/s41586-021-03550-y)
- Tammeorg O, Nürnberg G, Niemistö J, Haldna M, Horppila J., (2020). Internal phosphorus loading due to sediment anoxia in shallow areas: implications for lake aeration treatments. *Aquatic sciences* 82(3), 1-10. DOI: <https://doi.org/10.1007/s00027-020-00724-0>
- Anderson, D. M., Glibert, P. M., & Burkholder, J. M., (2002). Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries*, 25(4), 704-726. DOI: www.doi.org/10.1007/BF02804901
- Paerl, H.W., Hall, N.S., Calandrino, E.S. (2011) Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Science of the Total Environment* 409, 1739-1745. DOI: www.doi.org/10.1016/j.scitotenv.2011.02.001
- Sellner, K.G., Rensel, J.E. (2018) Prevention, control, and mitigation of harmful algal bloom impacts on fish, shellfish, and human consumers. *Harmful Algal Blooms: A compendium Desk Reference*, 435-492. DOI: www.doi.org/10.1002/9781118994672.ch12
- Fenner, N., Freeman, C. (2011) Drought-induced carbon loss in peatlands. *Nature geoscience* 4, 895–900. DOI: www.doi.org/10.1038/ngeo1323
- O'Driscoll, C., McGillicuddy, E., Croot, P., Bartley, P., McMyler, J., Sheahan, J., Morrison, L. (2020). Tracing sources of natural organic matter, trihalomethanes and metals in groundwater from a karst region. *Environmental Science and Pollution Research*, 27(11), 12587-12600. DOI: www.doi.org/10.1007/s11356-020-07855-9
- Leahy, P., Hermida, L., Gonzalez, K.H., Kiely, G., Allen, M., Parvaneh N., and Pasik, A., (2021). ClimAtt: Tools for Climate Change Attribution of Extreme Weather Events. EPA Research Project 384. Available at: www.epa.ie/publications/research/climate-change/research-384-climatt-tools-for-climate-change-attribution-of-extreme-weather-events.php
- Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S., Hanel, M., Kumar, R., (2022). The 2018–2020 Multi-Year Drought Sets a New Benchmark in Europe. *Earth's Future*, Volume 10, Issue 3. www.doi.org/10.1029/2021EF002394
- Meresa, H., Donegan, S., Golian, S. and Murphy, C. (2022) 'Simulated Changes in Seasonal and Low Flows with Climate Change for Irish Catchments', *Water*, 14(10), p. 1556. Available at: www.doi.org/10.3390/w14101556
- Kirkpatrick, Jennifer Isabel Munro, & Olbert, Agnieszka Indiana. (2020). Modelling the effects of climate change on urban coastal-fluvial flooding. *Journal of Water and Climate Change*. doi:10.2166/wcc.2020.166
- 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(9), pp. 5237–5257. www.doi.org/10.5194/hess-25-5237-2021

21. 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. DOI: [www.doi.org/10.5194/hess-25-1923-2021](https://doi.org/10.5194/hess-25-1923-2021)
22. 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(8), 803–818. DOI: [www.doi.org/10.1080/1573062X.2015.1036086](https://doi.org/10.1080/1573062X.2015.1036086)
23. Geris, J., Comte, J., Franchi, F., Petros, A.K., Tirivarombo, S., Selepeng, A.T., Villholth, KG., (2022). Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of Sub-Saharan Africa. *Journal of Hydrology* 609, 127834. DOI: [www.doi.org/10.1016/j.jhydrol.2022.127834](https://doi.org/10.1016/j.jhydrol.2022.127834)
24. Huebsch, M., Fenton, O., Horan, B., Hennessy, D., Richards, KG., Jordan, P., Goldscheider, N., Butscher C, Blum, P (2014) Mobilisation or dilution? Nitrate response of karst springs to high rainfall events. *Hydrology Earth System Science* 18, 4423–4435. DOI: [www.doi.org/10.5194/hess-18-4423-2014](https://doi.org/10.5194/hess-18-4423-2014)
25. Stevanović, Z., Stevanović, AM., (2021) Monitoring as the Key Factor for Sustainable Use and Protection of Groundwater in Karst Environments—An Overview. *Sustainability* 13(10), 5468. DOI: [www.doi.org/10.3390/su13105468](https://doi.org/10.3390/su13105468)
26. Morgan, D., Xiao, L., McNabola, A. (2017) Evaluation of combined sewer overflow assessment methods: case study of Cork City, Ireland. *Water and Environment Journal* 31(2), 202–208. DOI: [www.doi.org/10.1111/wej.12239](https://doi.org/10.1111/wej.12239)
27. Cámaro García W, Dwyer, N. (2021) Research 386: The Status of Ireland’s Climate, 2020. Environmental Protection Agency. Wexford. ISBN: 978-1-80009-009-5. Available at: www.epa.ie/publications/research/climate-change/research-386-the-status-of-irelands-climate-2020.php
28. Shoari Nejad, A., Parnell, A.C., Greene, A., Kelleher, B.P., McCarthy, G. (2020) Recent sea level rise on Ireland’s east coast based on multiple tide gauge analysis. *Ocean Science Discussions*, 1–26. DOI: [www.doi.org/10.5194/os-2020-81](https://doi.org/10.5194/os-2020-81)
29. Nolan, G., Cusack, C., Fitzhenry, D. (Eds), (2023). Irish Ocean Climate and Ecosystem Status Report. Marine Institute, Galway, Ireland, pp 192.
30. Moore, W.S., Joye, S.B. (2021) Saltwater Intrusion and Submarine Groundwater Discharge: Acceleration of Biogeochemical Reactions in Changing Coastal Aquifers. *Frontiers in Earth Science* 9, 600710. DOI: [www.doi.org/10.3389/feart.2021.600710](https://doi.org/10.3389/feart.2021.600710)
31. Environmental Protection Agency, (2022). Water Quality in Ireland 2016 – 2021. Report prepared by: Trodd W, O’Boyle S, Gurrie M (eds) Wexford, Ireland. Accessed on the 25th of October 2022. Available online: www.epa.ie/publications/monitoring--assessment/freshwater--marine/water-quality-in-ireland-2016--2021-.php
32. Environmental Protection Agency, (2022). Urban Waste Water Treatment in 2021. Wexford, Ireland. ISBN: 978-1-80009-063-7 Accessed on the 28th of December 2022. Available online: [Urban-Waste-Water-Treatment-in-2021-report.pdf \(epa.ie\)](https://www.epa.ie/Urban-Waste-Water-Treatment-in-2021-report.pdf)
33. EEA www.eureau.org/resources/briefing-notes/5111-briefing-note-on-the-impact-of-drought-on-drinking-water/file
34. Hammond, S., Rolston, A., Linnane, S., Getty, D. (2021). Communicating water availability to improve awareness and implementation of water conservation: A study of the 2018 and 2020 drought events in the Republic of Ireland. *The Science of the Total Environment*.
35. Water Forum, 2020. A Framework for Integrated Land and Landscape Management (FILLM). Available at: www.thewaterforum.ie/framework-for-integrated-land-and-landscape-management
36. Augustenborg, C.A., Kelleher, L., O’Neill, E. and Cloona, H. (2022). Insights from the 2018 Drought in Ireland’s Broadsheet Media, *Environmental Communication* 16:4, 445–457, DOI: 10.1080/17524032.2022.2063917
37. Cotterill, S., 2021. A Framework for Improving Domestic Water Conservation in Ireland. Research Commissioned by the Water Forum. Available at: www.thewaterforum.ie/app/uploads/2023/03/Water-Forum-Domestic-Water-Conservation-Policy-Brief-Final.pdf



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