POLICY BRIEF FOR AN FÓRAM UISCE

Addressing Projected Climate Change Risk to Water Quality in Ireland

Key Findings and Policy Recommendations for Ireland

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Executive Summary

There is growing concern surrounding the important linkages between water quality and climate change. This policy brief and full report was commissioned by An Fóram Uisce's Open Research Call with the aim of identifying where water and climate policies align and diverge with each other and with scientific evidence. The key findings and recommendations are outlined in this brief with regard to improving policy coherence for water quality management and climate change.

The availability of high-quality freshwater is crucial for enabling good public health, a functioning environment, and a productive economy. Over 80% of Ireland's water supply comes from surface waters (lakes, rivers, and streams), 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. Impaired water quality is a persistent and growing problem in Ireland, increasing costs associated with drinking water and food production, along with degrading ecosystems.

Extreme weather events are expected to include extended periods of abnormally low precipitation (droughts), rapid high-intensity precipitation events and flooding, along with increased heat waves and storm activity. In Ireland, observed changes in climate indicate that seasonal shifts in temperature and precipitation patterns are emerging across a clear west-to-east divide. Projected changes in seasonal precipitation suggest an increase in the frequency of rapid high-intensity precipitation events during the autumn and winter months, mostly affecting the south and west coast of Ireland. A substantial reduction in precipitation during the spring and summer months is projected, which will likely result in extended periods of water stress during the summer months, mostly affecting, but not exclusive to, the east and southeast of the country. The number of heatwave events are expected to increase over the 20-year period (2041–2060), with the largest increases in the southeast of the country. Furthermore, annual reduced river discharges, associated with increased low flow periods are already evident in the east and south of Ireland, while the midlands, west and north largely show a pattern towards increasing flows.

The quality of water will be affected at different times of the year and in different parts of the country. For example, heavy rainfall events could put pressure on water infrastructure, particularly for combined sewage overflow systems in urban areas (i.e., Dublin, Cork and Galway city). Ordinarily in urban centres all the waste water is treated before discharge; however, heavy rains can overwhelm combined sewage overflow systems by contributing additional stormwater, and in order to avoid sewers becoming overwhelmed in high rainfall events, excess water is discharged straight into local receiving waters, sending with it a cocktail of pathogens, active pharmaceutical ingredients, household chemicals, heavy metals, hydrocarbons, pesticides, excess nutrients, and other pollutants. The effect on water quality depends on a combination of climate change at the regional- to local scale, time of year (i.e., autumn and winter versus spring and summer months), population growth, and aging infrastructure. Conversely, reduced precipitation may lead to less dilution of contaminants present in water, resulting in the concentration of pollutant levels above 'Environmental Quality Standards' (EQS). In rivers and lakes, warmer summer temperatures may exacerbate the effects of eutrophication (excessive growth of plants and algae due to the increased availability of photosynthetic growing factors) and increase the abundance of cyanobacterial blooms. Some cyanobacteria produce cyanotoxins (secondary metabolites), which threaten the safe use of water for drinking and recreational (and even tourism) activities. A more complex scenario involves disentangling the combined impacts of temperature and precipitation change. For example, concentrations of organic carbon in streams and rivers draining upland peatlands have increased rapidly in recent decades due to a combination of changes in atmospheric deposition chemistry and peat degradation. The peatlands responsible for supplying high volumes of potable water in Ireland are all situated in upland areas (at least 300 m above sea level). Ireland consumes 0.19 km3 yr-1 of mixed-source peat-fed potable water, equivalent to supporting 4.22 million people in Ireland. Projected climate change (warmer temperatures and modified precipitation) to 2100 is predicted to cause severe degradation (drying) of peatlands, resulting in accelerated peat decomposition, release of aquatic carbon and a reduction water quality draining peat dominated systems. This will likely increase costs associated with disinfecting potable water in treatment plants, which will be required to not only remove organic carbon but also to mitigate the production of harmful disinfection by-products during the chlorination process, some of which are harmful to human health, such as trihalomethanes (THMs).

In addition to climate change, pressures from population growth and demographic and societal change (e.g. urbanisation, agricultural intensification), along with aging water infrastructure will compound existing pressures on the water sector. The population of Ireland has grown by 7.6% since 2016 and this growth is evident across every county. The impacts of climate change should inform investment in planning and ensure our infrastructure, and population, are more resilient to the realities of shifting regional weather patterns. It is essential that international initiatives, European legislation, and national strategies that promote policy responses to the water quality challenge are inclusive of climate change. This holds particularly true for the attainment of the 2030 Agenda and Sustainable Development Goals.

Effective action to integrate climate adaptation plans for water quality must be fully comprehensive to ensure the right measures are put in place to address the interconnected pressures of anthropogenic pollution, degradation of the quality of water, and climate change. To achieve this, coherence in policy documents and plans is essential. This requires identifying where water and climate policies align and diverge with scientific evidence. This information can be used to coordinate national efforts to maximise the capacity and impact of key national legislation to minimise the negative impacts of water quality in a warming world.

Recommendations

Acknowledgement

Recommendation 1.1: Identify and acknowledge risks where water quality will be impacted by climate change. The impacts of climate change on water quality should not be addressed in isolation. Drivers of water quality degradation (both individual pressures and climate change) should be addressed in tandem to adequately mitigate environmental impact.

Recommendation 1.2: The Climate Action Plan should be revised. The impacts listed in Box 21.1, Page 202 – Potential Impacts of Climate Change in Ireland, require a significant revision to provide an informed and comprehensive review. Impacts should be identified as 'expected' not 'potential' impacts.

Recommendation 1.3 The Climate Change Adaptation Plans for each sector should be revised and updated with measures where water quality is relevant to the various sectors. Table 10 in the main report outlines the current gaps.

Recommendation 1.4: The Water Quality and Water Services, Climate Change Sectoral Adaptation Plan should be revised and include the following;

- Increased lake water temperatures will alter thermal stratification patterns (lake mixing) resulting in major physical, chemical, and ecological effects in freshwater lakes and thus impacting on water quality, including an acceleration of lake deoxygenation with subsequent effects on nutrient mineralisation and phosphorus release from hypoxic and/or anoxic lake sediments.
- The impact of harmful cyanobacterial blooms on recreational activities
- Increased contamination and mobilisation of nutrients associated with rapid, high-intensity precipitation events and flooding should also be included for groundwater in karst regions.
- The drying of peatlands and the increase of DOC export to surface water systems should be included. Increased concentrations of DOC in freshwaters originating from peat soils have implications both for the ecology of receiving waters and for the quality and treatment costs of water used for human consumption.
- Atmospheric wet deposition of nutrients, particularly nitrogen and ammonium should be included as a pollutant source in surface waters
- Marine and freshwater acidification should be considered as a challenge for climate adaptation. Ocean and freshwater acidification will impact aquatic and marine ecosystems and subsequent food sources; while this cannot be mitigated at a local/regional level, adaptation of economically important species such as shellfish should be considered.

Recommendation 1.5: The National Water Resources Plan should be revised to include increased dissolved organic carbon export should be included as an additional barrier in the 'Drinking Water Safety Plan and Barrier Assessment approaches' section, due to associated disinfection-by-product issues with carcinogenic THM formation during the chlorination process. This will be a significant issue for water treatment functioning and cost with climate change.

Recommendation 1.6: Amendments need to be made to EU legislation (including Urban Wastewater Directive, Bathing Water Directive and Nitrates Directive) to adequately future-proof our water resources and aquatic ecosystems from the effects of climate change. These include:

- **Update needed for the Urban Waste Water Treatment directive,** Annex 1 "extreme values for the water quality in question shall not be taken into consideration when they are the result of unusual situations such as those due to heavy rain". Climate change projections include increased frequency and intensity of rapid, high-intensity precipitation events and flooding for Ireland and the EU, therefore 'heavy rain' will no longer be an 'unusual event', highlighting the necessity to revise this directive.
- Additionally, in the **Urban Waste Water Treatment directive**, Annex II, "a marine water body" is considered a "less sensitive area". The recent EPA report on Water Quality in Ireland shows a significant decline in transitional (estuarine) and coastal waters, which indicates that they are sensitive areas.
- Warmer water temperature associated with climate change will exacerbate the formation of harmful cyanobacterial blooms in standing waters. This factor should be included in the management of **Bathing Water Quality Directive** (2006/7/EC), Annex III bathing water profile.
- The Protection of waters against pollution caused by nitrates from agricultural sources (**Nitrates Directive** 91/676/EEC) does not consider surplus nitrogen pollution, which is volatilised into the atmosphere from chemical fertiliser application. Atmospheric nitrogen deposition is a significant extra-regional nutrient source through wet deposition; the exclusion of this process is a fundamental oversight. The lack of inclusion of climate change as an influencing variable on various water-related directives is highlighted in Table 5.

Integration

Recommendation 2.1: Develop an integrated cross-sectoral approach with all stakeholders.

Coordinated long-term national strategies for sustainably managing water in the face of climate change must look at water quality and quantity in a holistic way through collaboration with other sectors that develop policies and plans for activities that pose threats to water security.

Recommendation 2.2: National policies should be reviewed and updated to ensure climate action and climate adaptation measures account for impacts on water quality. Government officials responsible for the River Basin Management Plan 2022-2027, Water Quality and Water Services, Climate Change Sectoral Adaptation Plan, Climate Action Plan 2021 and the Nitrates Action Plan should consult and engage with one another for better alignment, with supporting input from the EPA and latest research (Higher Education Institutes).

Recommendation 2.3: There should be better alignment between the Climate Action Plan and the Sustainable Development Goals SDGs:

- SDG targets such as 14.3 ocean acidification, 14.2 protect and restore ecosystems, 14.5 conserve coastal and marine areas and 14.8 increase scientific knowledge, research and technology for ocean health should also be included.
- The Life On Land SDG (15) should also include the following relevant targets, 15.5 Protect Biodiversity and Natural Habitats, 15.8 Prevent invasive alien species on land and in water ecosystems, and 15.9 Integrate ecosystem and biodiversity in governmental planning.
- Various other SDGs relate to the anticipated impacts of water quality from current and projected climate change, including SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production).

Communication

Recommendation 3.1: Improve communication and synergies between government bodies and other stakeholders. Government departments, higher Education Institutes, regional authorities and consultancies should work together to develop innovative and tailored practical solutions for water and climate related issues.

Recommendation 3.2: Increase transparency in roles and responsibilities among government bodies, state agencies, non-government organisations and any other relevant stakeholders, to ensure accountability for action for climate adaptation measures relevant to water.

Research

Recommendation 4.1: Conduct research to fill knowledge gaps on water quality and climate change. Provide technical guidance based on science. Funding should be allocated and research calls expedited to address strategic priority relevant to increasing knowledge on climate change impacts on water quality in Ireland.

Recommendation 4.2: Future research on the exacerbated effects of eutrophication and the presence of cyanobacterial blooms relating to warmer temperatures and modified precipitation. This will have implications for water quality (reduced dissolved oxygen levels, light penetration and increased alkalinity of the water), aquatic organisms (biodiversity) and human health (aquaculture and recreational activities).

Recommendation 4.3: Future research on the anticipated impacts of dissolved organic carbon (DOC) from organic soils and peatlands due to climate change will impact 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.

Recommendation 4.4: Future research on the influence of atmospheric wet deposition of nutrients e.g. nitrogen and ammonium and subsequent enrichment should be included. The increased nutrient influx will exacerbate the effects of eutrophication and the prevalence of harmful cyanobacterial blooms, amongst other aquatic ecosystem alterations impacting water quality and restoration plans of water bodies.

Recommendation 4.5: Additional research on the impact and projections for:

- groundwater quality (monitoring) in karst regions, regional/local sea level rise monitoring and enhanced understanding of storm activity in Ireland
- extent of saline intrusion in vulnerable groundwater drinking water sources
- chloroform and trihalomethane (THM) formation in response to climate change
- marine and freshwater acidification impacts on water quality and aquatic ecosystems

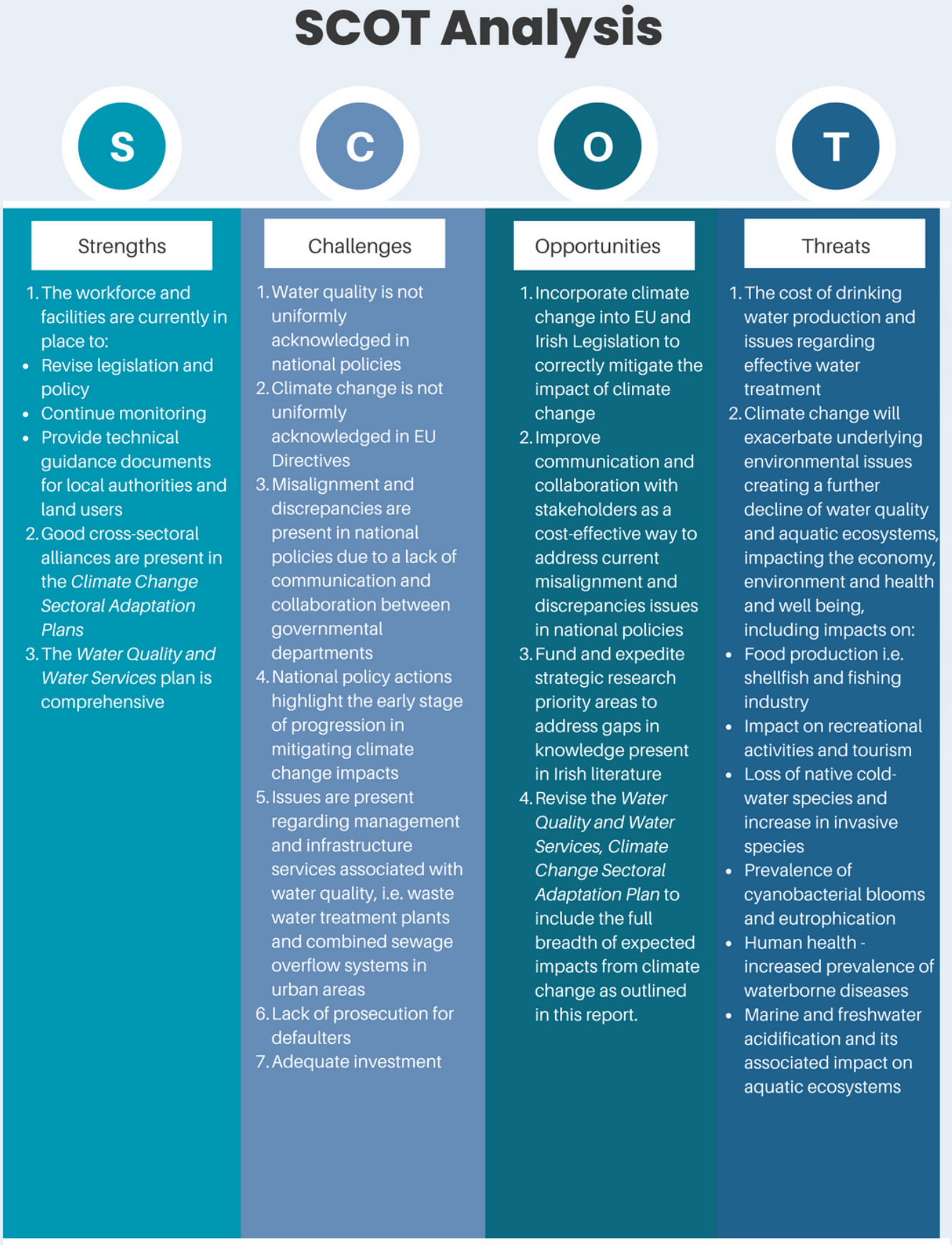

Figure 2. SCOT analysis highlighting the strengths, challenges, opportunities, and threats for water quality in Ireland, based on the findings of this report.

Scientific Context – Climate Change in Ireland

Ireland's climate is changing in line with global trends (IPCC, 2021). Surface air temperature has increased by approximately 1.1°C from pre-industrial levels (IPCC, 2021; Kaufman and McKay, 2022). The Intergovernmental Panel on Climate Change (IPCC) has predicted with high confidence that global temperatures will further increase at a rate of 0.2°C (likely between 0.1°C and 0.3°C) per decade (IPCC, 2021). In addition to warmer surface air and water (freshwater and marine) temperatures, the IPCC Sixth Assessment Report AR6 WII (IPCC, 2022) and the Climate Status Report for Ireland (EPA, 2021) predict changes in seasonality and precipitation patterns, increased incidence of extreme weather events and a gradual continued rise in sea level in Ireland. Extreme weather events are expected to include extended periods of abnormally low precipitation (i.e., droughts), rapid high-intensity precipitation events and flooding, heat waves, storms, and associated storm surge events, along with a reduced frost season and decreased snowfall in Ireland (Nolan and Flanagan, 2020).

In Ireland, observed changes in climate indicate that seasonal shifts in temperature and precipitation patterns are emerging across a clear west-to-east divide. Projected changes in seasonal precipitation show marked shifts, with a 20% increase in the frequency of rapid high-intensity precipitation events during the autumn and winter months, mostly affecting the south and west coast of Ireland (Nolan and Flanagan, 2020). The number of 'wet days' (> 20mm of daily precipitation) is expected to increase by between 10% to 14%, while the number of 'very wet days' (> 30mm of daily precipitation) is expected to increase by between 21% to 31% (Nolan and Flanagan, 2020). A substantial reduction in precipitation during the spring and summer months is projected, which will likely result in extended periods of water stress (Steele-Dunne et al., 2008; EPA, 2020). Projections anticipate a 20% to 27% increase in the number of 'dry periods' (< 1mm of precipitation daily, over a 5-day period) during the summer months, mostly affecting, but not exclusive to, the east and southeast of the country (Nolan and Flanagan, 2020). The number of heatwave events are expected to increase over the 20-year period (2041–2060), with the largest increases in the southeast of the country. Furthermore, annual reduced river discharges, associated with increased low flow periods are already evident in the east and south of Ireland, while the midlands, west and north largely show a pattern towards increasing flows. Increases in winter storm surge events along the Irish coastline will occur along the west and east coasts of Ireland (Wang et al., 2008). Global sea levels are expected to increase between 0.43 m and 0.84 m. Accurate projections for storm activity and sea-level rise are limited for Ireland.

Climate Change Impacts on Water Resources

Climate projections indicate that water resources will be affected both in terms of water quality and quantity. Projected changes in air temperature and rainfall could affect river flows and, hence, the mobility and dilution of contaminants. Warmer temperatures may alter thermal stratification regimes in surface waters, and may also exacerbate the effects of eutrophication, and potentially increase the frequency of harmful cyanobacterial blooms. This could have implications for recreational activities and the Irish tourism industry. Climate change could alter the prevalence of waterborne diseases and exacerbate disinfection issues for safe drinking water with implications for human health and water treatment costs. The anticipated impacts of climate change on water quality should be explored against the background of a growing population and changing societal demographics (i.e., urbanization).

Air and Water Temperature

- Increased air and water temperature will directly and indirectly affect surface water bodies (fresh and saline) physically, biologically, and chemically.
- Shallow lakes and wetlands will be particularly susceptible to increasing air and water temperature due to large surface-to-volume ratios (Feuchtmayr et al., 2009).
- Altered seasonal thermal stratification in lakes and coastal waters can affect dissolved oxygen levels, sediment suspension, along with altering nutrient and metal release from sediments – such as phosphorus and manganese (Tammeorg et al., 2020; Anderson et al., 2002). This could be a major issue for reservoirs and lakes were water is extracted for human consumption as manganese cannot be removed efficiently at water treatment plants.
- Exacerbated effects of eutrophication and increased frequencies of cyanobacterial blooms (which will further reduce dissolved oxygen levels, light penetration, and increase pH of water) will likely affect fishing and recreational activities (IPCC, 2022; Nazari-Sharabian et al., 2018).
- Loss of native cold-water species due to altered thermal regimes (Morato et al., 2021).
- Human exposure to waterborne pathogens may differ substantially from the current pattern due to the impact of climate change (Islam et al., 2021). However, the relative influence of climatic factors on pathogen concentrations remains poorly understood (Hofstra, 2011).

Extended Periods of Abnormally Low Precipitation (i.e., Droughts)

- Modified precipitation and infiltration patterns may lead to less dilution of contaminants present in surface and subsurface water, increasing the concentration of pollutants above Environment Quality Standards (Mellander and Jordan, 2021; Rosenfeld et al., 2011)
- Nutrients and contaminants may accumulate in soils during dry periods, which will eventually be released in higher concentrations through pulse events and during periods of rapid high-intensity precipitation events (Van Metre et al., 2016).
- Export of dissolved organic carbon and particulate organic matter in organic rich soils (such as peatlands) will likely increase due to drier conditions. This will exacerbate disinfection by-product (DBPs) issues in drinking water, such as the formation of carcinogenic trihalomethanes (THMs) (Fenner and Freeman, 2011; O'Driscoll et al., 2018).

Increased Frequency of Rapid High Intensity Precipitation Events and Flooding

- Increased frequency of rapid, high- intensity precipitation events (particularly for the autumn and winter months). This will likely (re-)mobilise contaminants, sediments, and waterborne pathogens from land to water or from one water system to another (i.e., stream to coastal system) (Geris et al., 2022; Huebsch et al., 2014).
- Rapid, high-intensity precipitation events, after extended dry periods, will be particularly harmful due to the accumulation of high concentrations of soluble contaminants in soils particularly after dry periods.
- Water quality of surface and subsurface water bodies will be affected, particularly groundwater in vulnerable karst regions (Stevanović and Stevanović, 2021).
- Ordinarily in urban centres all the waste water is treated before discharge; however heavy rains can overwhelm combined sewage overflow systems by contributing additional stormwater, and in order to avoid sewers becoming overwhelmed in high rainfall events, excess water is discharged straight into local receiving waters, sending with it a cocktail of pathogens, active pharmaceutical ingredients, household chemicals, heavy metals, hydrocarbons, pesticides, excess nutrients, and other pollutants (Morgan et al., 2017). Thus, polluting surface waters and may have negative effects for bathing waters (public health) and the seafood industry in Ireland.

Impacts Associated with Gradual Sea Level Rise and Storm Surge Events

- Expected to cause saline intrusion in some coastal aquifers and estuaries, which may affect groundwater drinking water resources. (Moore and Joy, 2021). Saline intrusion will compromise drinking water quality by increasing total dissolved solids (TDS) concentrations, altering the biogeochemistry of the aquifers and increased corrosion of buried infrastructure, with implications for water treatment.
- While only a small proportion of Ireland's coastal aquifers are exploited for potable water, almost half of all registered Irish hotels and B&Bs are located within five kilometres of the coastline (Fáilte Ireland, 2018). Saline intrusion in coastal aquifers would limit the potential to tap into groundwater reserves in the future for the tourism industry.

Other Associated Impacts

- Increased dissolution of anthropogenic carbon dioxide (CO2) from the atmosphere in surface waters causes ocean and freshwater acidification.
- Lower pH levels will alter water geochemistry and threaten food webs, the physiology of aquatic organisms and overall biodiversity (Arneth et al., 2020; Doney et al., 2020).
- Lower pH levels will contribute to the solubilisation of sediments and contaminants including trace elements (e.g., aluminium, lead, copper and cadmium) impacting water quality. Implications for human health and drinking water management, along with negative impacts on aquatic organisms that have narrow ecological optima and tolerances (Millerno et al., 2009; Peng et al., 2009).

SELECTED REFERENCES

Arneth A, Shin YJ, Leadley P, Rondinini C, Bukvareva E, Kolb M, Midgley GF, Oberdorff T, Palomo I, Saito O (2020) Post-2020 Biodiversity Targets Need to Embrace Climate Change. Proceedings of the National Academy of Sciences 117(49) 30882. DOI: https://doi.org/10.1073/pnas.2009584117

Doney SC, Busch SD, Cooley SR, Kroeker KJ (2020) The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities. Annual Review of Environment and Resources 45(1), 83-112. DOI: https://doi.org/10.1146/annurev-environ-012320-083019

EPA (Environmental Protection Agency) (2020) Ireland's Environment – An Integrated Assessment 2020. Report prepared by: Wall B, Cahalane A, Derham J (eds) EPA, Wexford, Ireland. ISBN: 978-1-84095-953-6. Available at: https://www.epa.ie/publications/monitoring--assessment/assessment/state-of-the-environment/EPA_Irelands_Environment_2020.pdf

EPA (Environmental Protection Agency) (2021) Research 386: Climate Status Report for Ireland 2020. Report prepared by Walther CA, García C, Dwyer N (eds) EPA, Wexford, Ireland. ISBN: 978-1-80009-009-5. Available at: https://www.epa.ie/publications/research/climate-change/research-386-the-status-of-irelands-climate-2020.php

Fáilte Ireland (2018) open dataset "Accommodation" http://data.gov.ie/dataset/accommodation

Fenner N, Freeman C (2011) Drought-induced carbon loss in peatlands. Nature geoscience 4, 895–900. DOI: https://doi.org/10.1038/ngeo1323

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: https://doi.org/10.1111/j.1365-2664.2009.01644.x

Geris J, Comte J, Franchi F, Petros AK, Tirivarombo S, Selepeng AT, 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: https://doi.org/10.1016/j.jhydrol.2022.127834

Hofstra N (2011) Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. Current Opinion in Environmental Sustainability 3(6), 471-479. DOI: https://doi.org/10.1016/j.cosust.2011.10.006

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: https://doi.org/10.5194/hess-18-4423-2014

IPCC Sixth Assessment Report Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2022) Report prepared by: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Cambridge University Press. In Press. Available online: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Prepared by: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI. Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, DOI: 10.1017/9781009157896

Islam MM, Iqbal MS, D'Souza N, Islam MA (2021) A review on present and future microbial surface water quality worldwide. Environmental Nanotechnology, Monitoring & Management, 16, p.100523. DOI: https://doi.org/10.1016/j.enmm.2021.100523

Kaufman DS, McKay NP (2022) Technical Note: Past and future warming – direct comparison on multi-century timescales. Climate of the Past 18, 911–917. DOI: https://doi.org/10.5194/cp-18-911-2022

Mellander PE, Jordan P (2021) Charting a perfect storm of water quality pressures. Science of the Total Environment 787, 147576. DOI: https://doi.org/10.1016/j.scitotenv.2021.147576

Moore WS, Joye SB (2021) Saltwater Intrusion and Submarine Groundwater Discharge: Acceleration of Biogeochemical Reactions in Changing Coastal Aquifers. Frontiers in Earth Science 9, 600710. DOI: https://doi.org/10.3389/feart.2021.600710

Morato T, González-Irusta JM, Dominguez-Carrió C, Wei CL, Davies A, Sweetman AK, Taranto GH, Beazley L, García-Alegre A, Grehan A, Laffargue P (2020) Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic. Global Change Biology 26(4), 2181-2202. DOI: https://doi.org/10.1111/gcb.14996

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: https://doi.org/10.1111/wej.12239

Millero FJ, Woosley R, DiTrolio B, Waters J (2009) Effect of ocean acidification on the speciation of metals in seawater. Oceanography, 22(4), 72-85. DOI: http://www.jstor.org/stable/24861025

Nazari-Sharabian M, Ahmad S, Karakouzian M (2018) Climate Change and Eutrophication: A Short Review. Engineering, Technology and Applied Science Research 8(6), 3668-3672. DOI: https://doi.org/10.48084/etasr.2392

Nolan P, Flanagan J (2020) Report 339: High-resolution Climate Projections for Ireland - A Multi-model ensemble approach. Environmental Protection Agency. Wexford. Available at: https://www.epa.ie/publications/research/climate-change/Research_Report_339_Part1.pdf

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: https://doi.org/10.1007/s11356-020-07855-9

Peng JF, Song YH, Yuan P, Cui XY, Qiu GL (2009) The remediation of heavy metals contaminated sediment. Journal of hazardous materials 161(2-3), 633-640. DOI: https://doi.org/10.1016/j.jhazmat.2008.04.061

Rosenfeld PE, Feng LGH (2011) 16 - Emerging Contaminants. Risks of Hazardous Wastes, 215-222, DOI: https://doi.org/10.1016/B978-1-4377-7842-7.00016-7

Steele-Dunne S, Lynch P, McGrath R, Semmler T, Wang S, Hanafin J, Nolan P (2008) The impacts of climate change on hydrology in Ireland. Journal of Hydrology 356, 28-45. DOI: https://doi.org/10.1016/j.jhydrol.2008.03.025

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: https://doi.org/10.3390/su13105468

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

Van Metre PC, Frey JW, Musgrove M, Nakagaki N, Qi S, Mahler BJ, Wieczorek ME, Button DT (2016) High nitrate concentrations in some Midwest United States streams in 2013 after the 2012 drought. Journal of Environmental Quality 45(5), 1696-1704. DOI: https://doi.org/10.2134/jeq2015.12.0591

Wang S, McGrath R, Hanafin J, Lynch P, Semmler T, Nolan P (2008) The Impact of Climate Change on Storm Surge over Irish Waters. Ocean Modelling 25. 83-94. DOI: https://doi.org/10.1016/j.ocemod.2008.06.009