Proceedings of the 46th Annual Groundwater Conference

Tullamore Court Hotel

April 14th & 15th 2026

International Association of Hydrogeologists (Irish Group)

Introduction

Now in its 50th year, the IAH (Irish Group) was founded in January 1976 and has grown from 10 members to over 150, and draws individuals from professional backgrounds ranging from academic to state agencies to private consultancies. The IAH committee consists of: President, Secretary, Treasurer, Burdon Secretary, Northern Region Secretary, Fieldtrip Secretary, Education & Publicity Secretary, Conference Secretary, plus a conference sub-committee.

Regular activities of the Irish Group include our annual two-day conference, an annual weekend fieldtrip, and a series of monthly lectures, technical meetings and training events and workshops. Funding for the association is derived from membership fees, the annual conference and the training events and workshops. We welcome the participation of non-members in all our activities. Other activities of the IAH (Irish Group) include submissions to the Irish Government on groundwater, the environment and matters of concern to members, organising the cataloguing of the Burdon library and papers that are now housed by Geological Survey Ireland, the invitation of a guest expert speaker to give the David Burdon Memorial Lecture on a topic of current interest in the field, and informing the broader research community through our social media channels and online newsletter.

The Irish Group also provides bursaries to students undertaking postgraduate degrees in hydrogeology and pays the annual subscriptions of a few members in other countries as part of the IAH's Sponsored Membership Scheme. If you would like to apply for a student bursary, details can be found on the IAH (Irish Group) website shown below. IAH are encouraging members to highlight their local IAH Group to their colleagues/ students and to invite anyone they feel may be interested to join.

The IAH (Irish Group) is also a sponsoring body of the Institute of Geologists of Ireland (IGI), and is a member of the Irish Geoscience Network.

For more information about the IAH (Irish Group) visit our website:

www.iah-ireland.org

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2026 IAH (Irish Group) Conference: Groundwater 2036: *Building Resilience for the Next Decade*

On behalf of the Irish Group of the International Association of Hydrogeologists (IAH), I am pleased to welcome you to the 2026 Annual Irish Hydrogeology Conference, *Groundwater 2036: Building Resilience for the Next Decade*, in Tullamore on 14th–15th April.

This year's conference brings together a diverse community of practitioners, researchers, policymakers and students to reflect on the evolving role of hydrogeology in addressing some of the most pressing environmental and societal challenges of our time. As we look towards the next decade, the sustainable management of groundwater resources is increasingly central to climate resilience, water supply security, ecosystem protection, and global development. It also seems appropriate to be looking forward in the same year we celebrate the founding of the IAH (Irish Group) 50 years ago, in 1976.

The programme reflects this broad and forward-looking theme. Sessions on Future Challenges and Resilience and Groundwater Supply Development explore how we can adapt our understanding and management of water resources in the face of climate change, increasing demand, and infrastructure pressures. Contributions from national agencies, consultants and international experts highlight both the complexity of these challenges and the innovative approaches being developed to address them.

A strong emphasis is placed on the interaction between groundwater and the wider environment. The session on Peatland Restoration showcases the growing importance of hydrogeology in supporting ecosystem recovery and biodiversity objectives, while Emerging Pressures and Contaminants addresses critical issues relating to water quality, including PFAS, pharmaceuticals and disinfection by-products. These themes underline the need for integrated, catchment-based approaches that link science, policy and practice.

The conference also reflects the global dimension of groundwater challenges. The Global Development session highlights the role of hydrogeology in delivering sustainable water and sanitation solutions internationally, while the Burdon Lecture emphasises the importance of effectively communicating groundwater data to support decision-making.

Finally, the Research and Development session, alongside early career presentations and the environmental monitoring workshop, demonstrates the continued evolution of tools, technologies and methodologies within the profession. These contributions are essential to ensuring that hydrogeology remains responsive, innovative and impactful.

As Conference Secretary, I would like to thank all speakers, contributors and attendees for their participation, as well as the organising committee for their work in delivering this event. I hope this conference provides a valuable forum for knowledge exchange, discussion and collaboration, and contributes to shaping a resilient and sustainable groundwater future, as well as acknowledging and celebrating the journey that started 50 years ago.

Gerry Baker

IAH (Irish Group) Conference Secretary

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The IAH (Irish Group) would also like to acknowledge the support of the following members and organisations whose staff have worked on the committee of the IAH (Irish Group) throughout the year and helped organise the conference:

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Groundwater 2036: Building Resilience for the Next Decade

Programme Day 1: Tuesday 14th April

08:30 – 09:30	Conference Registration: tea, coffee & exhibits
INTRODUCTION	
09:30 – 9:40	Welcome & Opening Address: Ray Flynn (*President IAH Irish Group*)
SESSION I	**Future Challenges & Resilience**
9:40 – 10:20	**KEYNOTE**: Elisabeth Lictevout: *Towards a Sustainable & Equitable Groundwater Future* (IGRAC UNESCO)
10:20 – 10:55	Billy O'Keefe: *Accounting for Climate Change in TII's Standards and Guidance – implications for surface water and groundwater assessments.* (TII)
11:55 – 11:05	*Q&A*
11:05 – 11:35	*Tea & Coffee*
SESSION II	**Groundwater Supply Development**
11:35 – 12:05	William McKnight: *Uisce Éireann's Supply Demand Balance Programme* (Uisce Éireann)
12:05 – 12:30	Katie Tedd: *Assessing Groundwater Abstraction Streamflow Depletion* (GSI)
12:30 – 12:50	Paul Wilson: *Hydrogeological Problem-Solving for Future Water Supply Resilience* (BGS)
12:50 – 13:00	*Q&A*
13:00 – 14:00	*Buffet lunch in Tullamore Court Hotel*
SESSION III	**Peatland Restoration**
14:00 – 14:25	Corrado Grappiolo: *European Ground Motion Service Data, Sentinel-2 Imagery and Artificial Intelligence: Application for Irish Raised Bog Ecohydrological Mapping* (Ai2Peat)
14:25 – 14:50	Bryan Irvine: *Developing a Standard for Ecosystem Certificates to Reward Funding for Irish Peatlands* (Peatland Finance Ireland)
14:50 – 15:10	Eliana Marin: *Implementation of Digital Tools for Peatland Characterisation* (ARUP)
15:10 – 15:20	*Q&A*
15:20 – 15:50	*Tea & Coffee*

SESSION IV	**Global Development**
15:50 – 16:20	Jerry Grant & Malcolm Edger: *Water-Share Ireland: A GOAL Global Programme: Delivering Water & Sanitation Projects In Developing Countries* (GOAL Water Share Ireland)
16:20 – 16:50	Kirsty Upton: ***2026 Burdon Lecture****: The Power of a Map: Translating Groundwater Data to Decisions* (BGS)
16:50 – 17:00	*Q&A*
17:00	*Posters & Wine Reception*
19:00	*Social event sponsored by IAH – Irish Group*

Programme Day 2: Wednesday 15th April

08:30 – 09:15	Conference Registration: tea, coffee & exhibits
SESSION V	**Emerging Pressures & Contaminants**
09:15 – 9:45	Jane Thrasher: *TFA – the emerging little PFAS raising some big questions* (Jacobs, UK)
9:45 – 10:10	John Weatherill: *Developing Monitoring Technologies & Assessment Techniques to Tackle THMs.* (UCC)
10:10 – 10:35	Jean O'Dwyer: *Assessing the Environmental Impact of Pharmaceutical Residues and the Rise of Resistance* (UCC)
10:35 – 10:45	*Q&A*
10:45 – 11:15	*Tea & Coffee*
SESSION VI	**Research & Development**
11:15 – 11:45	Michael McKenzie: *GEMINI and Groundwater Interactions of Geothermal Energy Development* (BGS)
11:45 – 12:05	Asma Slaimi: *River Water Level Prediction in Ireland: Comparative Forecasting and Leakage-Free Meta-Learning for Station-Aware Model Selection* (DCU)
12:05 – 12:25	Early Career Research Presentations
12:25 – 12:35	*Q&A*
12:35 – 12:50	*Conference Closing Address: Gerry Baker (Conference Secretary – IAH Group)*
13:00	*Buffet lunch in Tullamore Court Hotel*
	Optional Add-On Training Session
14:00 – 16:30	*Environmental Monitoring: Hands on Workshop*

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SESSION VI: Research & Development

SESSION I

TOWARDS A SUSTAINABLE & EQUITABLE GROUNDWATER FUTURE

Elisabeth Lictevout

IGRAC, Delft, The Netherlands

ABSTRACT

Groundwater is vital to humans and ecosystems, yet it is largely affected by anthropogenic activities, including groundwater extraction, contamination, land use change and climate change. Those pressures have modified groundwater processes and behaviour leading to changes in long-term groundwater quantity and quality trends. Monitoring groundwater levels and quality is essential to understand these changes and manage the resource sustainably. The analysis of 20-year time series of groundwater levels distributed across a range of climatic, geographic, hydrogeological and socioeconomic contexts worldwide shows a global overview of quantitative groundwater status and trends. Globally, groundwater levels show a mix of declining and rising trends, however, at regional scale, patterns and hotspots are evident, highlighting that the natural groundwater dynamic has been disrupted. Both rising and falling groundwater levels have substantial impacts on water and food security, ecosystems, infrastructure and socioeconomic wellbeing. So, do the adverse impacts of groundwater use and human activities outweigh the benefits? Understanding and analysing the impacts at different scales can support decision-making on which impacts are acceptable, which are not, thus supporting the estimation of sustainable groundwater extraction. On the other hand, analysis of cases of groundwater levels recovery unveils the actions that triggered a positive outcome. The extent of the impacts of groundwater level change changes in so many aspects of life underscores the urgent need to integrate and mainstream groundwater in development plans, to protect groundwater for human and ecosystem health, to develop coherent policies, adopt integrated approaches, cooperate beyond border, and strengthen capacity development and monitoring.

Key words: *groundwater long-term trends, groundwater monitoring, groundwater depletion and recovery, sustainable and equitable groundwater use.*

ACCOUNTING FOR CLIMATE CHANGE IN TII'S STANDARDS AND GUIDANCE – CHALLENGES FOR SURFACE WATER AND GROUNDWATER.

Billy O'Keeffe
Transport Infrastructure Ireland, Parkgate Street, Dublin 8.

ABSTRACT

Embedding climate change considerations into designs and environmental assessments is essential for ensuring resilient infrastructure. Transport Infrastructure Ireland (TII) is responsible for delivering the national road network, light rail, and cycleways. Mitigating climate-change impacts by lowering greenhouse gas (GHG) emissions during construction can be achieved through various measures, such as minimising earthworks and using materials with lower carbon footprints. Another mechanism for mitigating GHG emissions involves carbon offsetting, for example through the rehabilitation of peatlands.

TII has developed the necessary calculation tools to quantify these impacts (including the TII Carbon Tool and the TII Road Emissions Model, REM), which support efforts to reduce GHG emissions.

Adapting to climate change requires an understanding of how future climatic projections will affect infrastructural projects. Key parameters of concern for TII include pluvial, fluvial, and coastal flooding. TII is actively engaged in this assessment process, and a detailed research study carried out in collaboration with Met Éireann's TRANSLATE team examined the implications of climate change for the design of drainage systems, including both conveyance and attenuation infrastructure. The findings highlight the importance of undertaking a robust and detailed assessment before implementing any changes to drainage standards.

Key words: *Water Assessment, Climate Change, Standards, Drainage design.*

INTRODUCTION

Transport Infrastructure Ireland (TII) is responsible for the delivery of major infrastructure projects including National Roads, Light Rail and Cycleways. Embedding the effects of climate change into engineering design elements and future proofing TII's assets is key to deliver resilient infrastructure. Under current legislation TII have a remit to produce standards that must be complied with in relation to construction of national road projects. These standards can be used to ensure implementation of adaption measures and mitigation policies in relation to climate change. Many of TII's previously published environmental guidance documents are now standards. However, it is not always possible to simply have a standalone standard document for these environmental disciplines and in many cases the standard document is accompanied by an overarching technical guidance document (OTD). The choice of appropriate methodologies and survey requirements are subjective and heavily reliant on the competent expert. The OTD gives advice on the appropriate methodologies and survey requirements. It is essential that these surveys are proportionate to the scale of the project and the nature of the receiving environment. Mitigating (lowering greenhouse gas emissions) and adapting to climate change (building resilient infrastructure) are key priorities in these standards and technical guidance documents. This short paper will outline how TII account for mitigation and adaption but will also focus on the types of environmental assessments that are required to understand the effects of climate change with a particular reference to groundwater and surface water. The water aspects of the original NRA guideline on the treatment of geology, hydrology and hydrogeology is now replaced with a standard and OTD. A new standard for soils and geology is in development. Two case studies are discussed

related to opportunities for carbon offsetting and adaptation through peatland rehabilitation and the design of conveyance systems in light of climate change.

EMBEDDING CLIMATE CHAGE INTO TII'S POLICIES AND STANDARDS – OVERVIEW

TII SUSTAINABILITY IMPLEMENTATION PLAN

TII's Sustainability Plan (tii-sustainability-implementation-plan-2024.pdf) underpins TII's approach to developing a sustainable approach to all TII's activities. It forms the basis for developing and justifying any new standard and research. There are only 6 principles, they are measurable, easily understandable and most importantly achievable (Figure 1). Before embarking on any new project, the first key element is how and which of the 6 key principles will the project deliver on. Climate change and building resilience are essential elements of the plan.

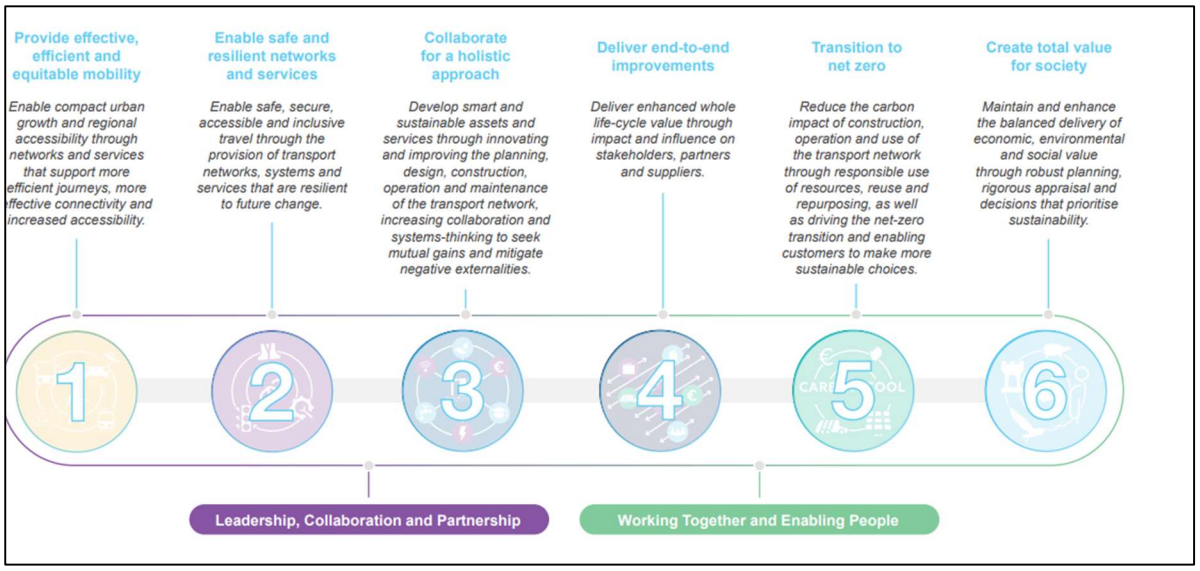

***Figure 1**: TII's Sustainability Implementation Plan - 6 Principles*

TII CLIMATE ADAPTATION STRATEGY AND OVERARCHING TECHNICAL GUIDANCE DOCUMENT

TII's Climate Adaptation Strategy (climate-adaptation-strategy-2022_v2.pdf) outlines how TII will manage our assets going into the future. The core of the strategy involves an initial high level screening risk assessment of the different asset groupings covering road, light rail, cycleways but also land, people and buildings. This is complete and published. The next phase is a detailed assessment of the asset groupings identified as being at risk and the development of implementation plans. This is currently underway.

TII CLIMATE ASSESSMENT STANDARD AND OVERARCHING TECHNICAL GUIDANCE DOCUMENT

TII's Climate Assessment Standard (PE-ENV-01105) and OTD gives a more detailed approach on how to assess climate mitigation and adaption measures in road, light rail and cycleways projects through TII's project phases. It also outlines the required project deliverables for each of the phases.

***Table 1**: Example of required deliverables from TII's Climate Standard*

Climate Assessment Actions Required	How to Implement
Phase 0 – Scope and Pre-Appraisal (TII)	
• Align with local and national climate policy. • Apply NIFTI investment hierarchies. • Input findings into relevant documents including: Strategic Assessment Report, Project information Summary Notices, and Phase 0 Gate Review Statement.[3]	• Examine local and national policy in relation to climate change and identify whether the project scope is in keeping with policy, in relation to GHG emissions and climate risk. • Critically assess the need for infrastructure. A prioritisation of sustainable modes of travel should take place; explore the rationale behind the project and whether opportunities for sustainable modes of travel e.g. Rural Cycleways (Offline & Greenways) and cycle paths can be accommodated via pragmatic application of the NIFTI intervention and modal hierarchies.
Phase 1 – Concept & Feasibility (TII)	
• Describe the greenhouse gas and climate impacts of the project. • Describe mitigation and adaptation principles and opportunities. • Input into relevant documents including: Project Execution Plan, Phase 1 Gate Review Statement, Feasibility/Constraints Report, etc.	• Define the purpose and scope of the assessment. • Identify the existing local conditions for reasonable alternatives and any difference between them that may impact GHG and/or climate risk. **GHG Assessment** • Describe the potential GHG impacts of the project on the climate, with any differences in the long list of options identified. Differences in options which have a significant bearing on the carbon emissions impact should therefore be deduced. These include land use types traversed, type(s) of infrastructure, length of infrastructure. • Discuss mitigation principles and opportunities with the Design Team. • CCR Assessment Describe historic climate events for the project location.

TII'S WATER STANDARD DOCUMENT AND OVERARCHING TECHNICAL GUIDANCE DOCUMENT

TII's new Water Standards (PE-ENV-01201 published December 2025) outline how to bring climate change elements into designs and the planning process and develop on from all the above by embedding the principles of climate change and projections into the requirements for the assessment of surface water and groundwater (Table 1). Climate related assessment is just an individual but important component of the assessment process. The required data for these assessment processes is reliant on climate projection data (e.g. RCP 4.5, RCP 8.5 medium and worse case scenarios). In general projections for long duration rainfall storm events with return periods of e.g. 1:100 years or projected coastal levels are reasonably well detailed to allow for inclusion in the assessment process, and these factors are applied for assessment. However, shorty duration intense rainfall events are not so well established, but these events are critical for the design of conveyance systems. This will be discussed below.

TII'S NEW WATER STANDARD DOCUMENT AND OVERARCHING TECHNICAL GUIDANCE DOCUMENT – OVERVIEW

WATER STANDARD DOCUMENT

This Standard PE-ENV-01201 shall be used on national road projects to assess the potential water (hydrological and hydrogeological) impacts. This Standard supersedes the hydrology and hydrogeology aspects of the former National Roads Authority (NRA): Guidelines on Procedures for Assessment and Treatment of Geology, Hydrology and Hydrogeology for National Road Schemes (2009).

- To outline the approach to the assessment of water (hydrological and hydrogeological) effects during the planning and design of national road projects, motorway service

areas, toll schemes, and any associated infrastructure, hereafter referred to as national road projects.
- To apply the water assessment in a manner that is proportionate to the complexity, scale, and likely significance of water environment effects of a national road project.
- To deliver consistency in approach to the consideration and description of the water (hydrological and hydrogeological) environment and to the assessment and mitigation of likely significant effects resulting from all phases of national road projects.
- To encourage production of documents and deliverables which meet the requirements of the TII PMGs/PAGs, EIA Directive and other relevant legislation, policies, guidelines and standards.
- To promote a context-sensitive approach to the design of appropriate mitigation and monitoring measures for likely significant effects of national road projects.

OVERARCHING TECHNICAL GUIDANCE

This “Overarching Technical Document” (OTD) (PE-ENV-01202), provides guidance on best practice methodology for undertaking water (surface, estuarine, coastal and groundwater) impact assessments for Specified Infrastructure Projects (national roads, light rail, metro and rural cycleways projects (offline and greenways)).

The purpose of the Overarching Technical Guidelines is to provide a key reference for the methodologies and theory underlying water environment assessment in accordance with, and building on, Ireland’s policy requirements, guidelines and best practice (Figure 2).

- To set out the principles and processes underlying the water (hydrological and hydrogeological) assessments.
- To provide guidance on the methodology for undertaking water (hydrological and hydrogeological) assessments to ensure consistent and appropriate description and evaluation of the receiving environment.
- To promote an assessment approach that is proportionate to the complexity, scale, and likely significance of water environment effects.
- To provide guidance on the methodology for assessing hydrology and hydrogeology for the planning and for the design and assessment phases of delivering TII projects.
- To promote a context-sensitive approach to the design of appropriate mitigation and monitoring measures for likely significant effects.

CONSIDERATION OF OTHER ENVIRONMENTAL DISCIPLINES

When undertaking environmental evaluation including EIA for the hydrogeology and hydrology disciplines, it is important to recognise that there is overlap with other disciplines. There is also the potential for mitigation measures to affect other disciplines, and collaboration is required to identify and assess these effects. Cross-discipline cooperation is also required to ensure consistency in the presentation of risks and receptors. Cross-discipline cooperation requires liaison and / or workshops between the various specialists at an early stage.

CASE STUDIES MITIGATION AND ADAPTATION ASSESSMENTS

DRAINAGE DESIGN – CLIMATE ADAPTATION ASSESSMENT.

Introduction

Conveyance systems such as carrier pipes and drained channels are designed based on short duration intense rainfall events, often in the region of 15 mins. Projections for this type of short duration rainfall events are not generally available through the normal projection platforms. TII engaged with Met Eireann and the TRANSLATE team to develop a research project (post - doc) to examine these types of events in Ireland with a view to determining the resilience of the national road network to changes to climate impacts on these short duration events. The

project was developed by UCC and the initial findings are published (https://www.sciencedirect.com/science/article/pii/S0301479724011952) and freely available.

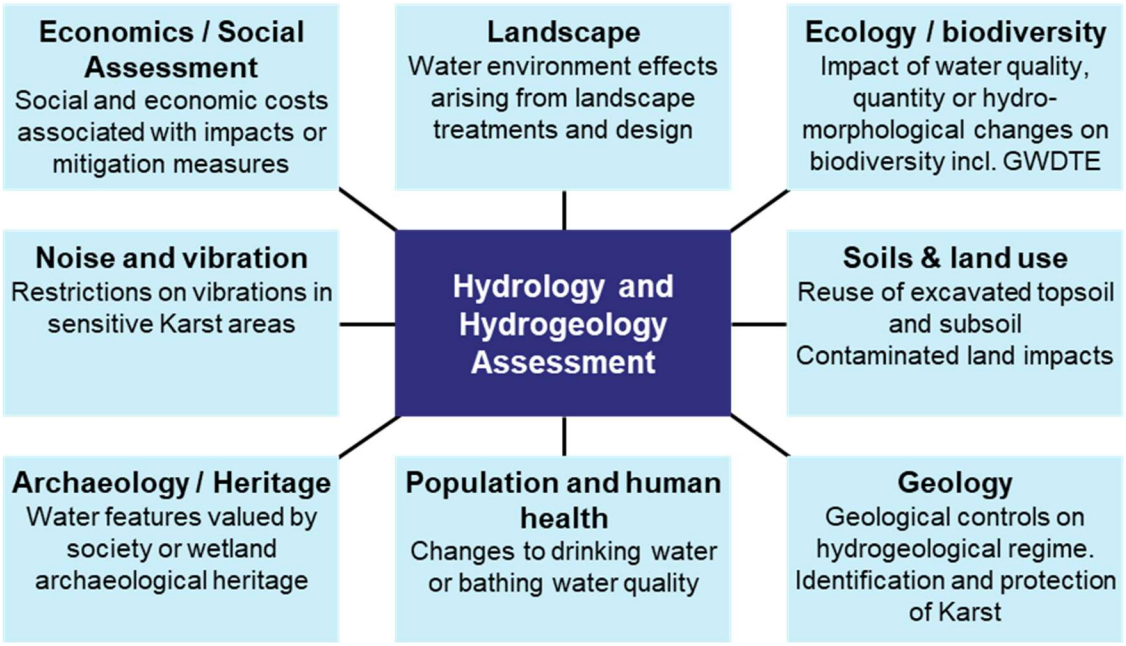

Figure 2: *Interactions from New Water Standard Documents*

The project introduces a practical and innovative way to estimate future high-resolution spatio-temporal precipitation projections with short durations from daily projections and past observation data at sub-daily or sub-hourly resolutions, e.g., future projections for storm events with 15 min duration.

The research also examined the sizing of the attenuation ponds. The default for TII drainage standards is to design for 1:100-year events. The capacity of these ponds was examined considering climate projections (Figure 4).

The approach was based on a probabilistic risk-based assessment framework and consisted of four steps 1) Examine existing and future hazard in relation to rainfall 2) Examine the current road drainage model designs and assess vulnerability 3) establish vulnerability to future climate impacts 4) Examine adaptation options.

Results and Implications

The research quantified the increase in inflows to the drainage systems looking at the two main projections scenarios RCP 4.5 and 8.5. This are the mid-range and high range scenarios that are used in most climate projection models across Europe. There are still large uncertainties but there is a consistent trend on increased inflows from the different projections. The implications for increased flooding based on our current drainage standards and sizing of pipes is also quantified and is graphically represented in Figure 3. The diagram shows an increased probability of flooding on the network. The increased probability is quantified in Table 2. Currently TII's drainage standards already include a climate factor of 20% increase in rainfall for conveyance and attenuation systems. This reduces the probability and the implications of using this climate factor is also shown in Table 2. The result is that we are still left with a residual increase in probability of flooding even with the 20% increase although much reduced. The sizing of attenuation systems shows a general trend of increasing inflows but as there are already engineering factors (300mm freeboard) and climatic factors embedded into the designs the results indicate that the likelihood of pond overflows retained zero reflecting the conservative nature of the design process. The next steps in this project

will be a cost benefit analyses to investigate in introducing new design standards for future projects is of benefit.

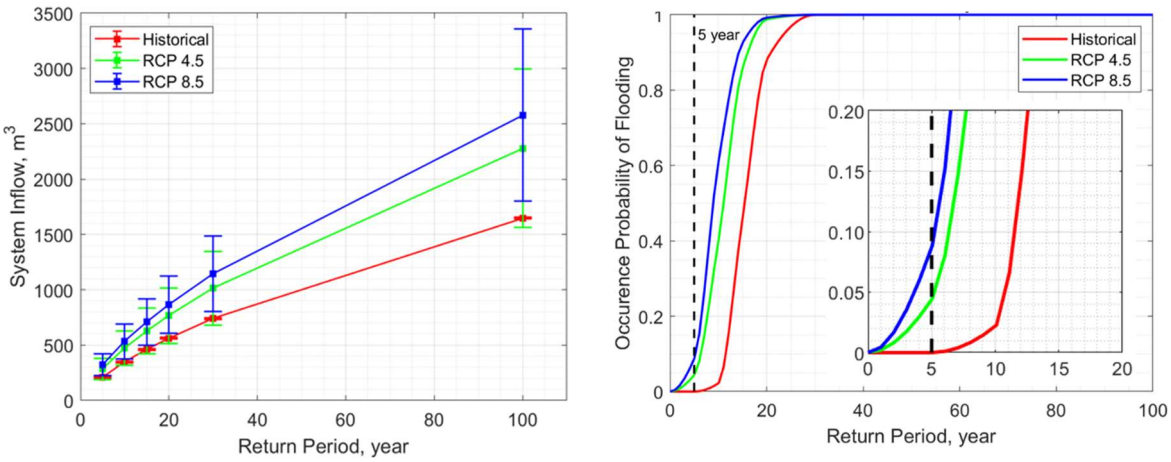

Figure 2: *Flows and probability of flooding for conveyance systems on national road* ***https://www.sciencedirect.com/science/article/pii/S0301479724011952***

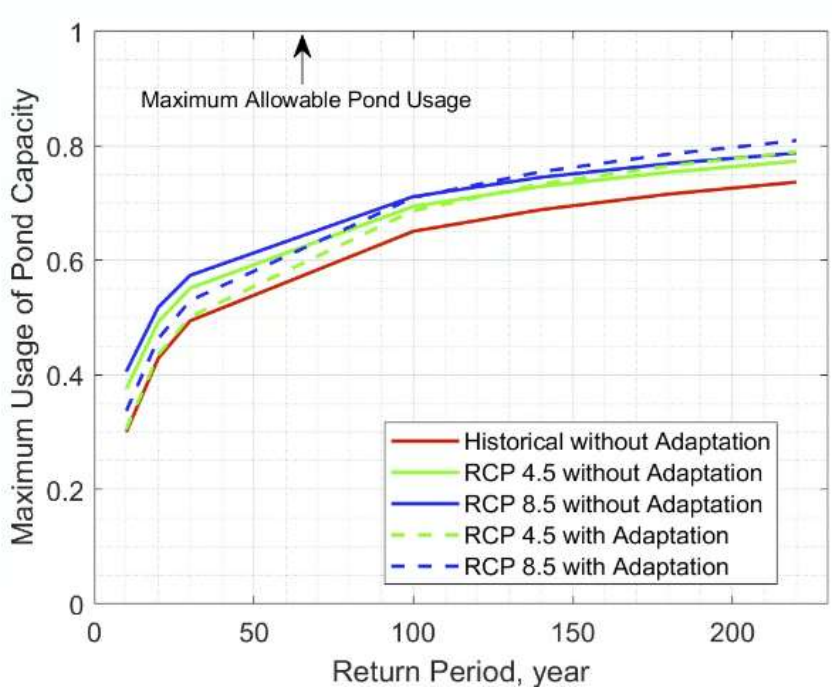

Figure 3: *Assessment of attenuation ponds capacity*
https://www.sciencedirect.com/science/article/pii/S0301479724011952

Table 2: *Quantification of the probability of flooding on conveyance systems*
https://www.sciencedirect.com/science/article/pii/S0301479724011952

Climate Change Scenario	**System Failures without Adaptation**	**System Failures with Adaptation**
	5-Year Return Period	5-Year Return Period
Historical	0	0
RCP 4.5	4.4	1.3
RCP 8.5	8.7	1.9

MITIGATING GHG EMISSIONS – PEATLAND REHABILITATION

Lowering greenhouse gas emissions using more sustainable, low-carbon materials during construction is a key objective for TII. TII's Carbon Tool enables the quantification of these emissions reductions, and TII's Climate Standard supports the incorporation of alternative low-carbon materials into project design.

In addition to reducing emissions at source, carbon offsetting is also an important mechanism for mitigating the environmental impacts associated with construction. TII has completed a detailed study of carbon emissions from the N22 road project (22 km mainline; total emissions approximately 150,000 tCO_2e), and a summary of these emissions is presented below.

Avoiding interaction with peatlands during the planning stages of linear infrastructure projects, such as roads, is a key priority. However, this is not always achievable, and in some cases interaction with degraded peatlands cannot be avoided. Intact peatlands are avoided wherever possible and are strongly protected under legislation.

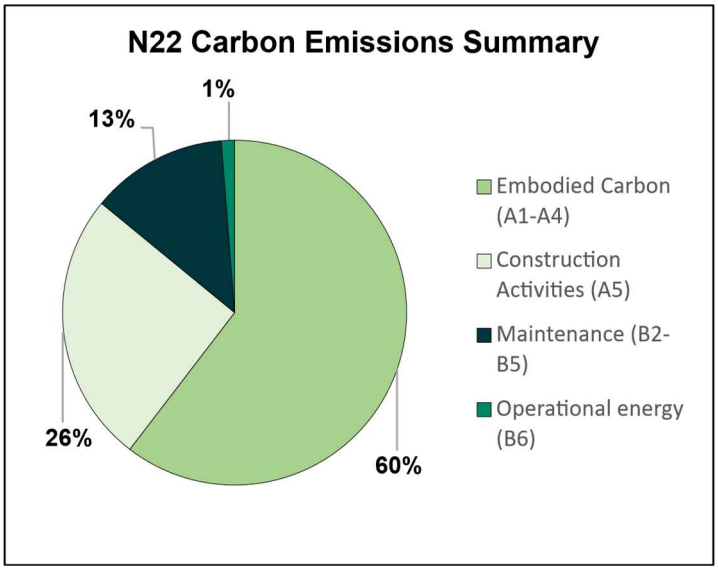

Figure 4: *Summary of Carbon Breakdown N22*

The biodiversity and carbon sequestration benefits of peatlands such as blanket bogs and raised bogs are well established. Where road projects travers degraded peatlands there are opportunities to develop mitigation measures that can lead to the rehabilitation of peatland habitats and/or the construction of new peatland deposition areas through the careful management of any surplus peat and rewetting of existing degraded areas.

TII have conducted a research project on the methodologies and opportunities for peatland rehabilitation over the last 3 years. The research identified peat deposition areas from previous project where careful engineering and management of the hydrology and hydrogeology of these areas led to the growth of sphagnum and a growing peatland habitat. The project also details the necessary surveys (hydrology, hydrogeology, ecology) required to identify which peatland habitats are suited to rehabilitation. The project identifies the necessary engineering solutions and the ecological indicators to monitor the rehabilitation progression. During construction of the N59 road project several peat deposition areas were constructed. The surrounding peatlands are heavily degraded. The deposition areas were engineered to manage water runoff and ensure rewetting of the peat. This resulted in the growth of sphagnum and a growing peatland habitat.

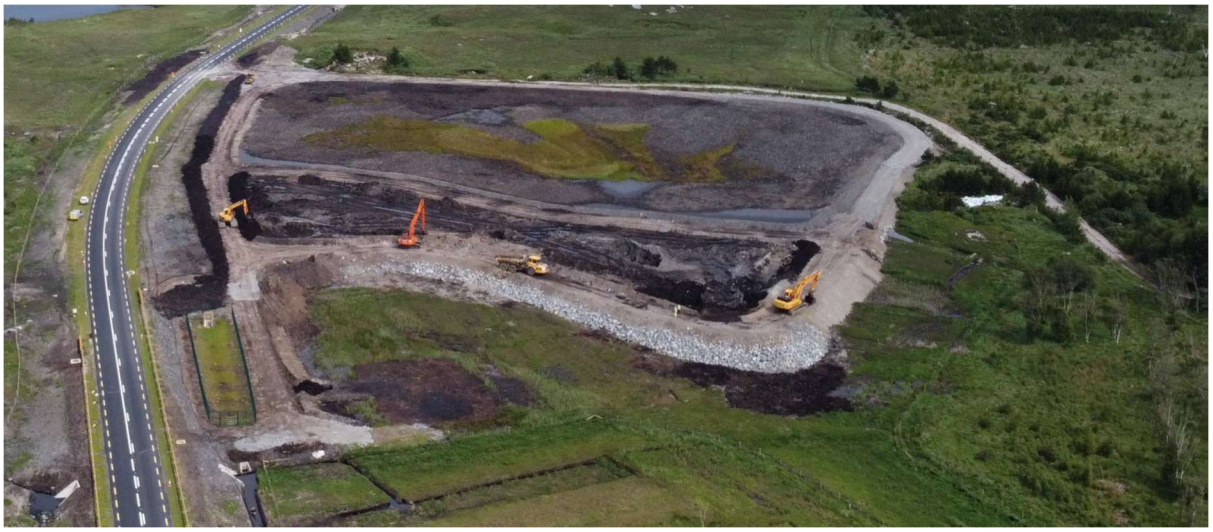

Figure 5: *N59 Peat Deposition Area*

SESSION II

UISCE ÉIREANN'S SUPPLY DEMAND BALANCE GROUNDWATER PROGRAMME

William McKnight
Infrastructure Delivery, Uisce Éireann

ABSTRACT

Groundwater resources currently provide 17% of total public water supply by volume and their development has typically been on a standalone basis. This paper gives a brief background to their development and outlines the current approach taken by Uisce Éireann (UÉ) under an investment programme known as the Supply Demand Balance (SDB) Groundwater Programme.

BACKGROUND

Prior to the formation of the State there had been drinking water infrastructure established only for towns and cities with piped water from surface waters to homes and businesses. The new State commenced improving the water supply to rural Ireland during the 1920-1930's with a programme which installed village pumps over shallow wells. During the 1940-1950's there was a gradual extension of this programme to the countryside. However poor siting and the shallowness of these early groundwater sources led to several public health crisis such as the Polio outbreak of 1957.

Following these public health outbreaks and to improve the quality of life the State made a policy decision to deliver piped water supply to rural Ireland however its abilities were severely constrained by the fiscal position throughout the 1960's. Unlike the rural electrification programme which by 1965 had connected 80% of rural households to the electrical supply only 3% of rural dwellers had access to a piped supply of water.

The entrance into the EEC in 1972 transformed the rural water sector with the higher price for agricultural produce leading to greater demand for sources of piped water and landowners opening their land to provide sources and sites for drinking water infrastructure.

The first phase of the new rural drinking water infrastructure was in the east and south of Ireland and was chiefly sourced from groundwater normally limited to one source per townland. By the early 1980's all but the most remote extents of rural Ireland had a piped water supply. However, over the decades since a lot of these original groundwater sources in particular springs have been vulnerable to intensified agricultural activity and have been replaced with deeper and more resilient boreholes.

Today's Public Water Supply has over 800 individual groundwater abstractions These abstractions are made of predominantly boreholes, approximately 140 springs and several infiltration galleries. The focus of investment in recent decades has been to achieve compliance with drinking water quality standards from these existing groundwater sources with new treatment and disinfection infrastructure.

SUPPLY DEMAND BALANCE GROUNDWATER PROGRAMME

UÉ's National Water Resource Plan (NWRP) which was completed in 2023 has identified how it will balance the supply and demand for drinking water over the next 25 years in each of the 539 Public Water Supply Zones (WSZ). Where the preferred solution is a new groundwater source then this new investment is now been delivered by the SDB Programme and the current interventions are illustrated in Figure 1 below.

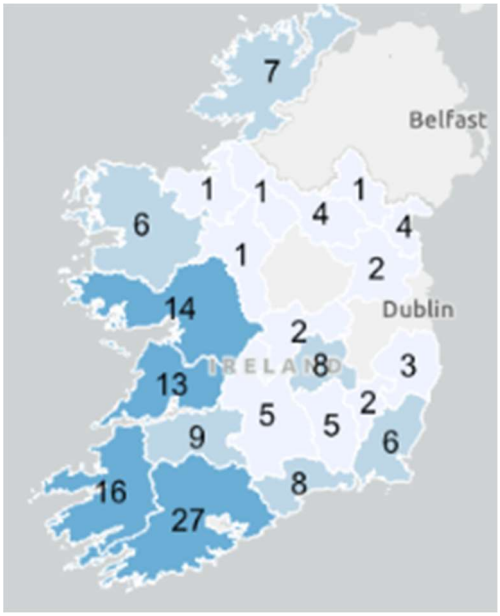

Figure 1: *SDB Programme WSZ locations*

A deficit in the SDB for a water supply zone is a term used that defines the following scenarios to UÉ:

- Nighttime operational restrictions whereby pressure is reduced in distribution networks to enable the refilling of upstream storage reservoirs to meet peak daily demands;
- Tankering treated water from water supply zones that have available capacity and emptying into storage reservoirs especially during drought periods;
- WSZ's closed to new connections for homes and businesses;
- Preliminary assessment that current abstraction volumes are not sustainable;
- Existing abstraction capacity not capable of meeting estimated future growth in the WSZ.

DELIVERY APPROACH

To achieve a successful new groundwater source that will address the deficit in the SDB there are several criteria that need to be aligned namely:

- Yield
- Quality
- Environmental
- Landowner
- Planning Consent & Abstraction License

1.Yield

This process is led by experienced hydrogeologists who initially complete a desktop assessment to confirm if there are sustainable aquifers within the water supply zone that can meet the specified deficit volume.

For several WSZ's across the country these assessments of impacts from abstracting additional volumes on the groundwater body and surface water body balances have concluded against proceeding to exploration phase e.g. Ballyshannon Co. Donegal and UÉ progressing an alternative surface water option to address the SDB deficit.

In other cases, this assessment concluded that new sources of groundwater would only partially address the deficit e.g. Letterkenny Gravels could only yield an additional 1MLD of

the 7MLD actual deficit and the balance will be met by transferring treated surface water from the Eddie Fullerton Dam which is located north of Bundoran on the Inishowen peninsula.

Figure 2: *Eddie Fullerton dam completed in 1997 to supply Buncrana Co. Donegal*

Contrasting with these experiences has been the positive to address the South Wexford deficit of 12MLD with exploration ongoing at Adamstown Co. Wexford.

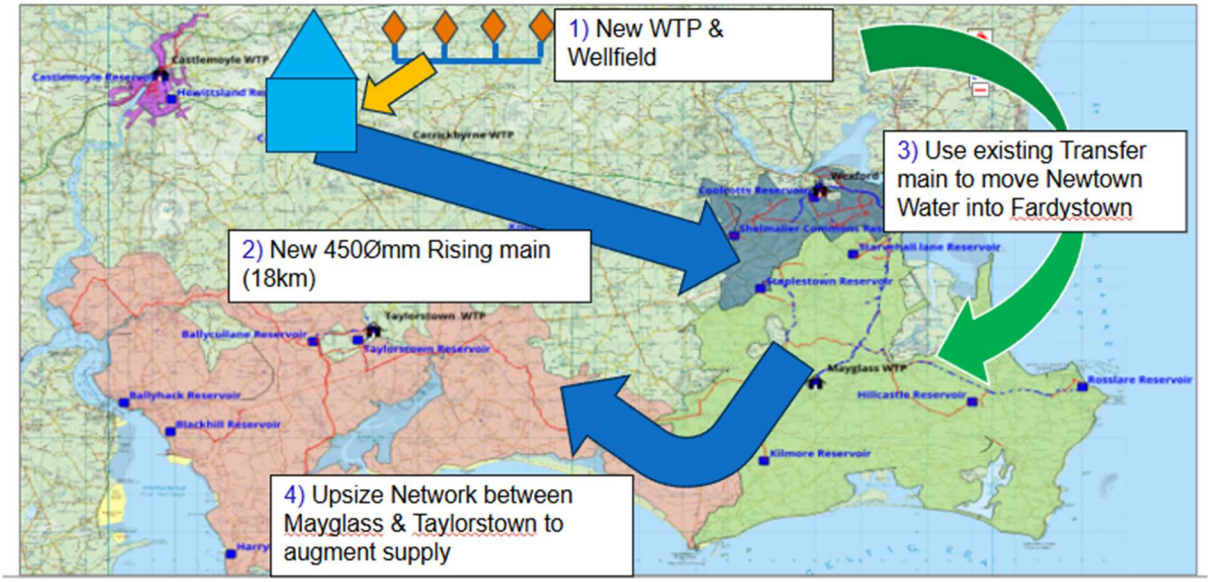

Figure 3: *New Groundwater Sources at Adamstown Co. Wexford and proposed infrastructure*

2.Quality

Raw water quality monitoring during pumping testing of new boreholes is a well-established practice however in some cases the characteristics of the groundwater have seasonal variations which may not be identified during this phase of sampling.

To mitigate raw water quality variation impacting the design & build phase the SDB programme has extended raw water monitoring of new sources to an entire calendar year to continuously measure Ultraviolet Transmittance (UVT) and additional chemical & biological sampling in response to variations in UVT. An example of this approach was at Gowran Co. Kilkenny which was recently completed to address a 2MLD deficit where the levels of iron & manganese doubled from the sampling during the borehole Pumping Test phase to later during the 12-month period. To achieve compliance with drinking water standards significant treatment infrastructure was required as follows:

- 3 No. Dual Media Pressure Filters for first stage iron removal
- 3 No. Manganese Dioxide Pressure Filters for second stage manganese removal
- Prefiltration chlorination for oxidation for both first and second stage filtration
- Ultraviolet Primary Disinfection

- Chlorination Secondary Disinfection
- Backwashing infrastructure for both sets of filters
- Lamella thickener with clarified liquid residuals return to raw water balancing tank

Figure 4: *Completed Water Treatment Plant at Gowran, Co. Kilkenny.*

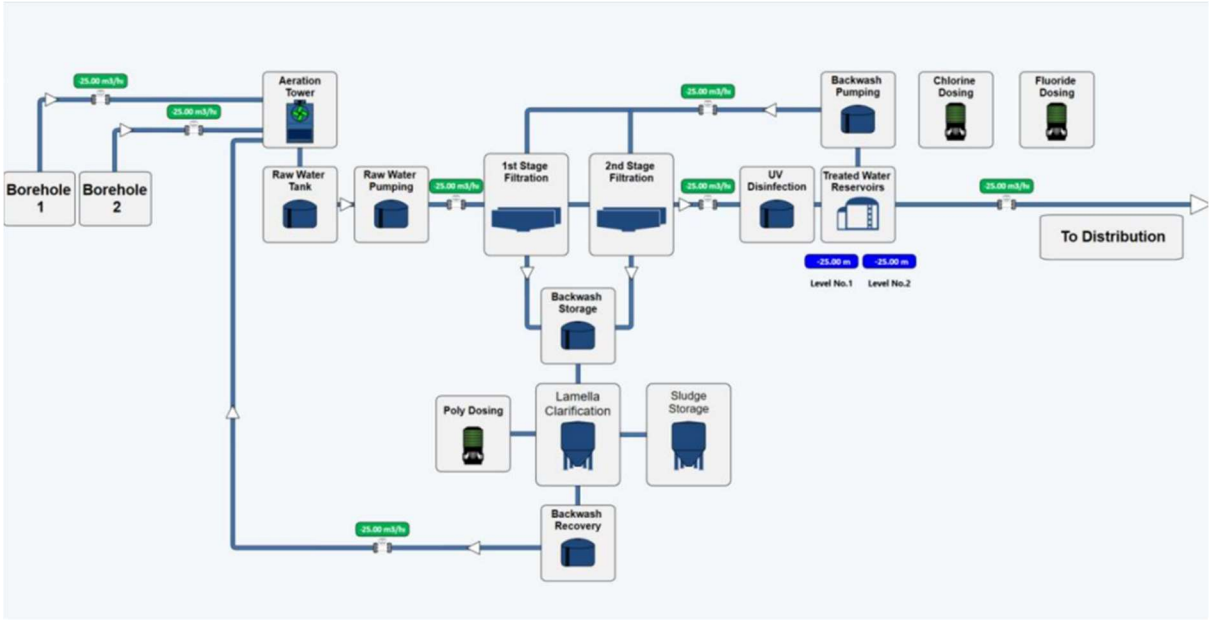

Figure 5: *Schematic of water treatment plant at Gowran, Co. Kilkenny.*

3.Environmental

Prior to the commencement of exploration drilling a walkover survey is carried out by the SDB's Ecologists to assess potential impacts. Due to UÉ's Strategy to achieve no nett loss of habitat, the SDB team avoid progressing exploration at locations with ecological value.

The focus during the exploration phase is to assess any potential impact on local surface water aquatic life from the water management process during Pumping Tests. This impact is eliminated in most sites by leasing generous amounts of local land and simply flooding it during this phase and avoiding any direct discharge to surface waters. There have been exceptions e.g. Castlecomer Co. Kilkenny during exploration of the sand & gravels along the River Dinin where it was unavoidable to discharge pumped water to the river following intermediate settlement.

In several locations where overflows from Springs occur additional fieldwork is underway to get an accurate record of flow characteristics especially low flows. An example in Figure 7 below where we have recently completed a one-year record of overflow from Longford Spring

with concurrent rainfall record. This data will enable an accurate surface water body test to be completed for the abstraction license application to the EPA.

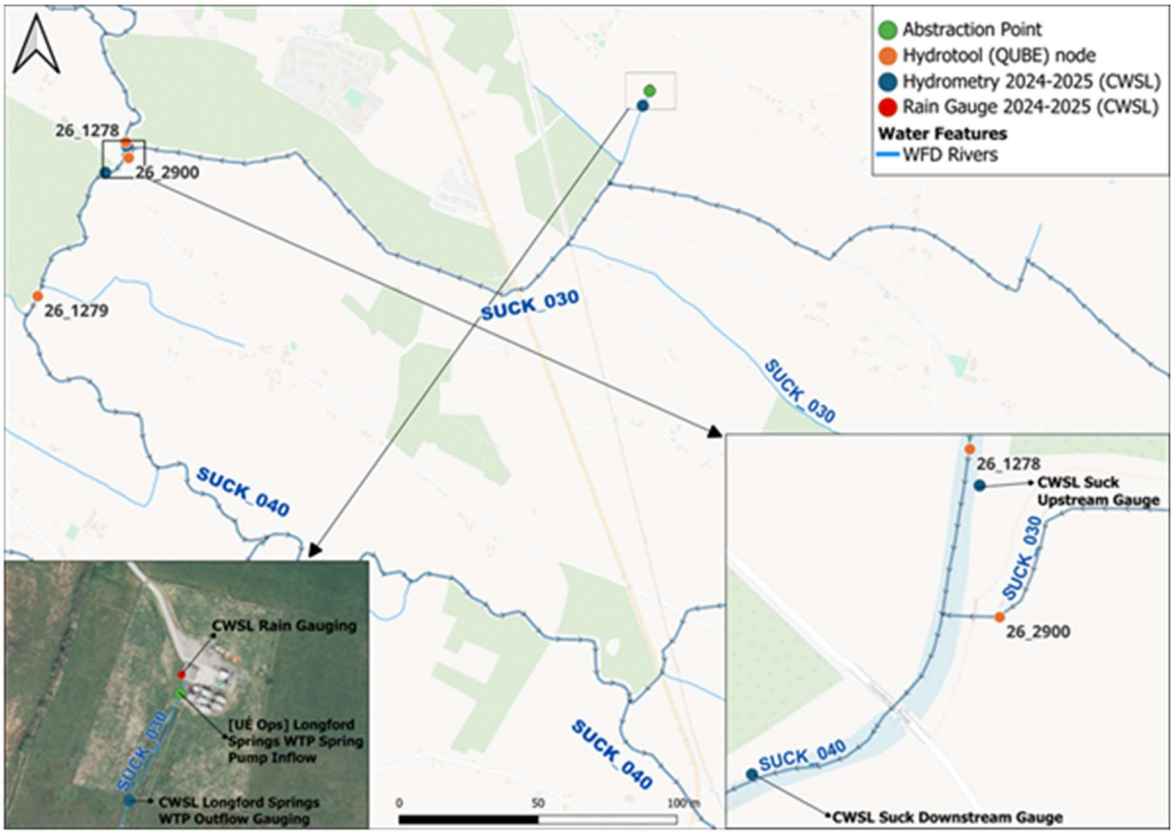

Figure 6: *Longford Spring at Castlerea WTP with locations of 12-month flow measurement*

4.Landowner

Over 98% of the proposed locations to progress exploration are in private lands and UÉ has encountered challenges throughout 2024 and 2025 in achieving agreement with landowners to facilitate exploration on their lands. A sample of landowner engagement recorded a variety of reasons for refusal, refer to Figure 7 below:

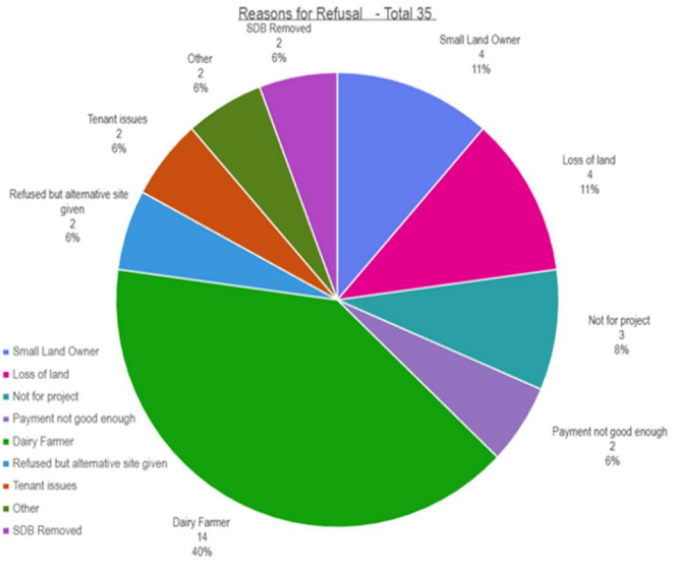

Figure 7: *Sample reasons for landowners to refuse permission for exploration by UÉ*

A refreshed process is now in operation which has been successful in getting agreement for all proposed borehole locations for 2026. The revised process is summarised as follows:

Following the identification of an area within a known aquifer that can meet the deficit 'white maps' are created.

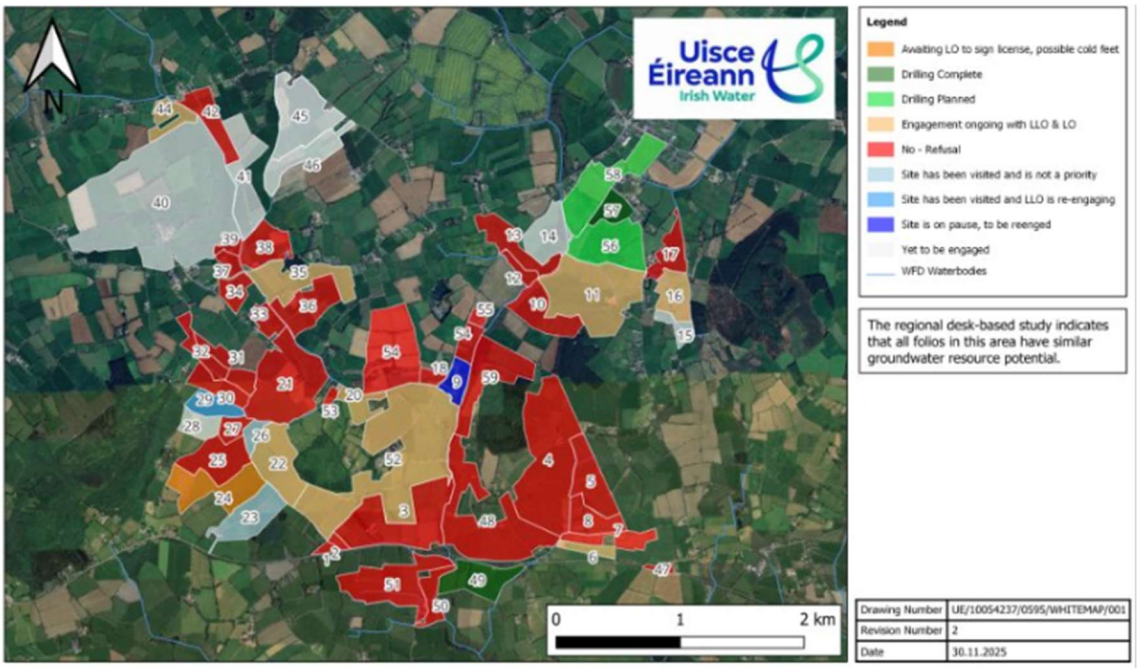

Figure 87: *'White Map' identifying folios within area of interest for exploration.*

These maps are used by the UÉ Land Liaison Partner (LLP) to seek expressions of interest from local landowners to facilitate the planned exploration works with a bias away from land that is farmed intensively. Once an expression of interest is received the UÉ SDB team inspect the specific site that is been offered to assess its constraints, and if suitable formal arrangements are then progressed between the landowner and UÉ to lease the required areas for the exploration period only which is limited to 6 months from date of entry with payment up front.

In the scenario where exploration is successful UÉ then seeks to acquire the land acquisition to a scale that can accommodate the range of infrastructure defined by UÉ in its Ground Water Abstraction Specification. During the land acquisition phase UÉ works with the Landowner on the application of the European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2017(S.I. No. 605 of 2017) which sets out restrictions on the land-spreading of farm fertilisers (organic and chemical) and soiled water close to the proposed new drinking water abstraction.

5.Planning Consent and Abstraction License

The exploration for new sources of groundwater for public water supplies by UÉ is classified as an exempted development in accordance with the *Planning and Development (Amendment) Regulations 2018*. The exemption does not apply if the project '*screens in'* for Appropriate Assessment which the Office of Planning Regulator guidance clearly advises:

"Any measure or feature of the development that is wholly or partially included in order to avoid or reduce impacts to European sites cannot be considered for the purposes of screening out the need for appropriate assessment." The measure in the case of groundwater exploration is often the necessary sediment removal process prior to discharge to a surface water during Pumping Tests.

If exploration has been successful UÉ applies to the Local Authority for a planning consent for the Project. Following a successful planning consent from the Local Authority, UÉ then submits

details of the proposed abstraction to the EPA in accordance with the Water Environment (Abstractions and Associated Impoundments) Regulations 2024 to demonstrate:

- No deterioration in WFD waterbody status
- No impact on protected site (SAC/SPA)

CONCLUSIONS

The SDB programme has a major role in improving rural drinking water infrastructure over the next decade and its success can only be achieved by technical expertise to deliver:

- Assessments of groundwater viability within the available aquifers
- Assessments of the potential environmental impacts of proposed abstractions
- Estimates of safe and sustainable yield from project concept to abstraction license application
- Designs of boreholes and onsite supervision of drilling, testing, sampling of trial and production boreholes
- Delineations of Zones of Contribution and risk assessing contamination in collaboration with UÉ and GSI

Similarly, UÉ's ability to identify landowners interested in supporting this important programme for rural Ireland and then addressing their concerns will determine how efficiently this vital infrastructure can be delivered.

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STREAMFLOW DEPLETION IN IRISH HYDROGEOLOGICAL SETTINGS

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ABSTRACT

Streamflow depletion is a reduction in streamflow caused by groundwater pumping. The total amount of streamflow depletion equals the sum of captured groundwater discharge and induced infiltration of streamflow. The most significant impacts of streamflow depletion are typically observed during low-flow periods. Accurate quantification of streamflow depletion is a critical component of water resource management. The recent introduction of Water Environment (Abstractions and Associated Impoundments) Act 2022 and associated regulations ensure that water abstractions are sustainable and are aligned with the environmental objectives of the EU Water Framework Directive. The legislation requires the quantification and understanding of streamflow depletion in Irish settings. This paper presents a thorough review of streamflow depletion estimation methodologies and their applicability in Irish aquifer settings carried out by Geological Survey Ireland (GSI). This paper presents selected results from the review and a tiered assessment framework (Table 2) which aims to facilitate the selection of appropriate methodologies for quantifying streamflow depletion.

Key words: *Streamflow Depletion, Groundwater, Water Resources, Abstraction.*

WHAT IS STREAMFLOW DEPLETION?

Streamflow depletion is a reduction in streamflow caused by groundwater pumping (Barlow et al., 2018). The total amount of streamflow depletion equals the sum of (i) the reductions in the outflow rate of groundwater from an aquifer (captured groundwater discharge – see Figure 1C) and (ii) increases in the inflow rate of streamflow to an aquifer (induced infiltration of streamflow - see Figure 1D). Although streamflow depletion refers specifically to streams, its use can include depletion of flow in other surface-water features including rivers, springs, and lakes. Figure 1 shows the development of streamflow depletion over time from a groundwater abstraction in an unconfined aquifer. For further information on streamflow depletion please see Barlow and Leake (2012) and Barlow et al. (2018).

IMPACTS OF STREAMFLOW DEPLETION

Streamflow depletion can affect both water users and aquatic ecosystems, with the most significant impacts typically observed during low-flow periods. Beyond the direct reduction in water quantity, streamflow depletion can indirectly influence stream conditions by altering water quality and temperature. For example, lower water volumes may reduce a stream's capacity to dilute pollutants or lead to increased water temperatures, both of which can modify the suitability of the habitat for various species e.g. Atlantic salmon are particularly dependent on cool groundwater inflows. This paper will focus on direct impacts on quantity of streamflow.

STREAMFLOW DEPLETION IN IRISH ABSTRACTION LEGISLATION

The implementation of the Water Environment (Abstractions and Associated Impoundments) Act 2022 and the associated 2024 regulations mark a significant update to water resource management in Ireland. Under this new regime, the Environmental Protection Agency (EPA) oversees a licensing system designed to ensure that water abstractions are sustainable and are aligned with the environmental objectives of the EU Water Framework Directive.

The Water Environment Act applies a graduated approach to the regulation of abstractions. Any abstraction equal to or greater than 2,000 m^3/day requires an abstraction licence. Any abstraction between 25 m^3/day and <2,000 m^3/day will be assessed by the EPA to determine

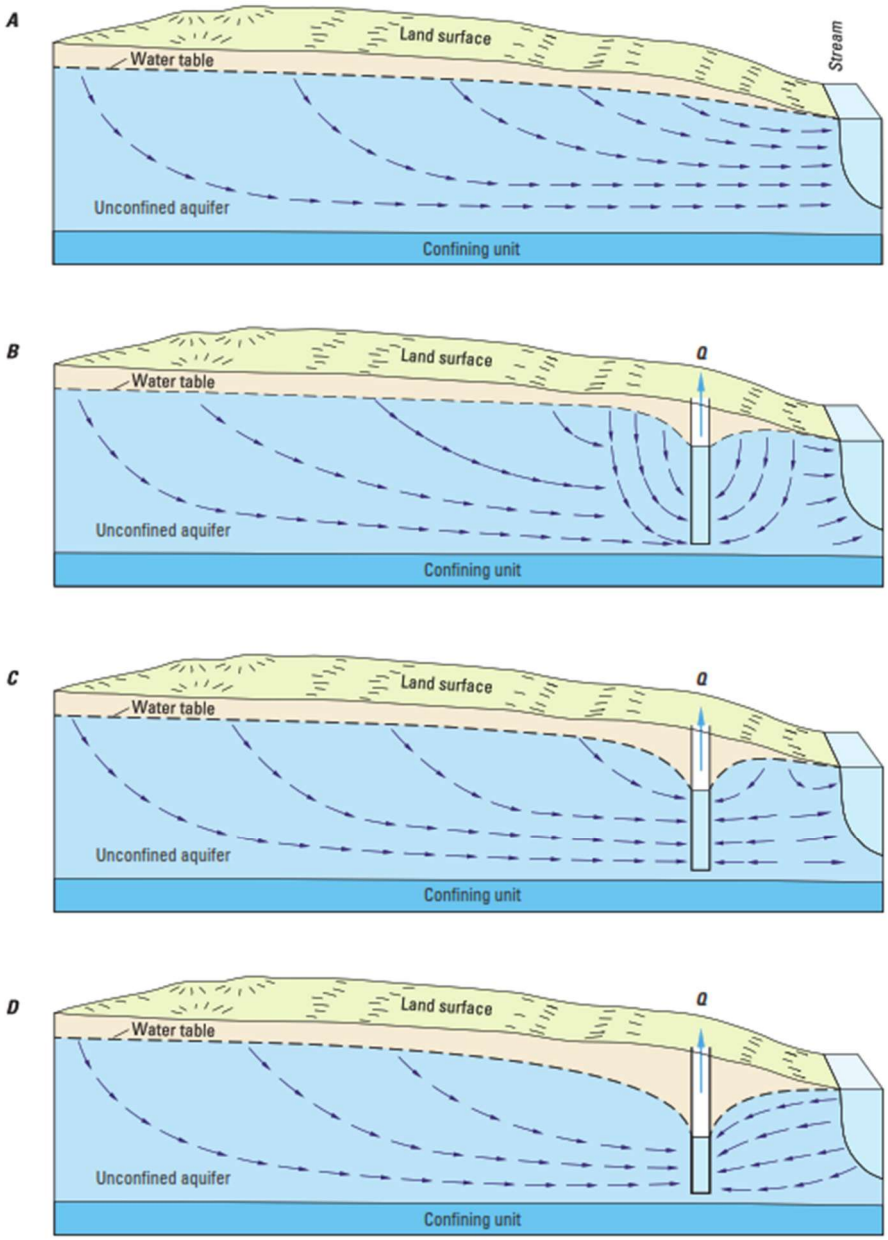

Figure 1: *Development of Streamflow Depletion in an unconfined aquifer after Barlow and Leake, 2012.*

A*: In this scenario an unconfined aquifer is depicted where groundwater naturally flows toward the stream, contributing to streamflow as baseflow.*

B*: As pumping begins, water is released from aquifer storage to satisfy the pumping rate. Groundwater flow in the aquifer remains similar to the conditions in stage A, while the cone of depression slowly begins to develop around the pumping well.*

C*: As pumping continues, the well begins to intercept groundwater that would otherwise have flowed toward the river -* ***"captured groundwater discharge"****. However, the cone of depression has not yet reached the stream, and groundwater continues to discharge to the river as baseflow.*

D*: Over time the cone of depression expands until it reaches the river. This reduces the hydraulic gradient between the aquifer and the river and may cause water from the stream to flow toward the pumping well –* ***"induced infiltration of streamflow"****. Reduced streamflow may fail to support environmental flows (eflows) that sustain healthy river ecosystems and dependent habitats. In extreme cases, streams may lose all their water to the aquifer, causing the stream to become ephemeral.*

if it is a significant abstraction. If an abstraction is deemed to be significant, an abstraction licence will be required (EPA, 2025).

According to the River Waterbody assessment, outlined in EPA (2025), an abstraction is classified as a Significant Abstraction if it fails a three-step evaluation process:

- Step 1 Hydrological limits: Within a catchment, does the cumulative impact of all abstractions cause a breach of hydrological limits (or an e-flow limit) in any river waterbody?
- Step 2 Spatial Analysis: Is the breach happening in more than 5% or 15% (High or Good Status objective respectively) of the length of any river waterbody?
- Step 3 The 1% rule: Are any individual abstractions between 25 and 1,999 m^3/day taking more than 1% of the volume of water which can be sustainably abstracted from an individual river waterbody?

The Groundwater Body Assessment comprises a series of chemical and quantitative tests to determine if a groundwater body is at "good status". Within the Groundwater Body Assessment, the “Impact on Surface Waterbodies” and the “Impact on supporting conditions of groundwater dependent terrestrial ecosystems (GWDTEs)” tests require the calculation of streamflow depletion for all abstractions between 25 m^3/d and < 2000 m^3/d (excluding listed exemptions). Once calculated the streamflow depletion caused by the groundwater abstraction will be considered as part of the cumulative surface water abstractions in Step 1 (above) of the River Waterbody test (or Lake Waterbody test).

HOW IS STREAMFLOW DEPLETION MEASURED OR ESTIMATED?

Streamflow depletion is extremely challenging to measure directly in real hydrological settings for several reasons. First, reductions in streamflow are superimposed on natural weather-driven variations in river discharge. Secondly, the impact of an individual pumping well on a particular river reach can be difficult to discriminate from other nearby abstractions and hydrological impacts. Third, the effects of pumping in an aquifer–stream system are characterised by a delayed response (Bredehoeft, 2011). For these reasons, analytical and numerical models have been developed to estimate how cones of depression evolve over time in different hydrogeological settings and to quantify volumetric streamflow depletion. For a review of past and emerging methods for quantifying streamflow depletion please see Zipper et al.. (2022).

HYDRAULIC DIFFUSIVITY

Analytical solutions suggest that two of the most important factors controlling the magnitude and timing of streamflow depletion are:

- the distance between the pumping well and the stream, and
- the hydraulic diffusivity of the aquifer.

Hydraulic diffusivity (D) is defined as the ratio of transmissivity (T) to storativity (S)

$$D=T/S \text{ [units: } m^2/d]$$

Hydraulic diffusivity is typically defined for confined aquifers; however, in unconfined aquifers it is often acceptable to use specific yield instead of the storage coefficient, provided that the change in saturated aquifer thickness caused by pumping is relatively small (typically less than 10% of the predevelopment saturated thickness). Aquifers with higher diffusivity values allow hydraulic stresses (not to be confused with groundwater movement) to propagate more rapidly through the system, whereas aquifers with lower diffusivity values exhibit slower hydraulic responses. Consequently, confined aquifers often have diffusivities that are several orders of magnitude higher than those of unconfined aquifers because their storage values are much smaller.

IRISH AQUIFER DIFFUSIVITY COMPARED TO INTERNATIONAL EXAMPLES

Hydraulic diffusivities were calculated for Irish aquifers using values of aquifer properties from Kelly et al.. (2015). Typically, Irish unconfined aquifers have mean hydraulic diffusivities ranging from approximately 420 m²/day in poorly productive aquifers to around 5,000 m²/day in Rkd[1] aquifers (see Figure 2). In comparison, reported diffusivity values from other countries such as the United States (Barlow and Leake, 2012), the United Kingdom (Allen et al.., 1997), Canadian (Rathfelder, 2016), Nordic countries (Banks et al., 2010) and New Zealand (Davidson and Wilson, 2011) are often significantly higher: in the range of 1,000s to 10,000,000s m^2/d (see Figure 2). This implies faster propagation of hydraulic stresses in those systems when compared to Irish systems.

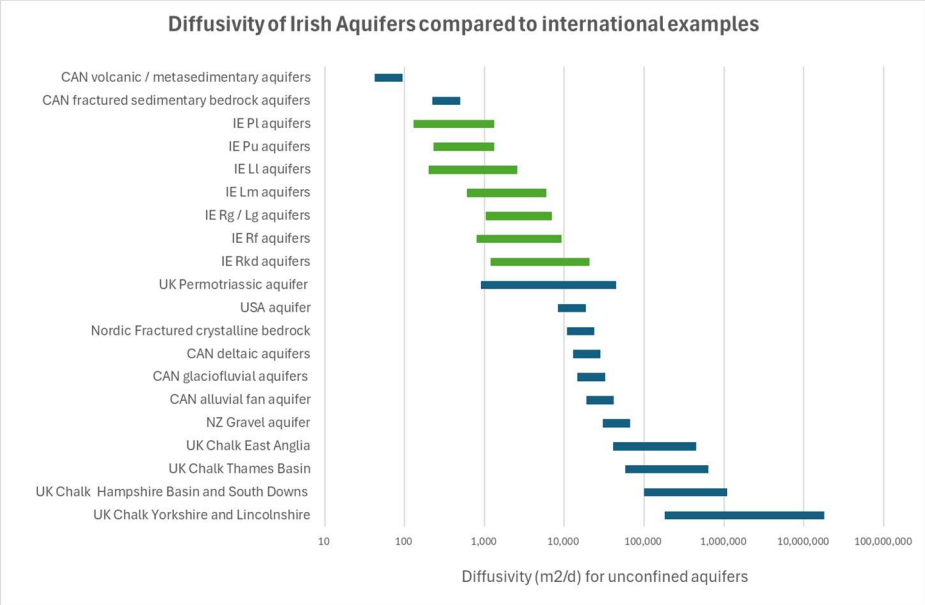

Figure 2: *A comparison of the diffusivity of unconfined Irish Aquifers (highlighted in green) compared to international examples. The range in Diffusivity values for each Irish aquifer type represents the range from 25th percentile to 75th percentile for that aquifer type's transmissivity (see Kelly et al., 2015). References for the international examples are given in the text. Values from Canada, USA, New Zealand represent single values; values from the UK represent a range from the 25th percentile to the 75 percentile where available.*

Groundwater in porous media aquifers tend to respond to hydraulic stress in a steady and predicable way. The response in fractured rock aquifers with little primary porosity (like Irish hydrogeological settings) tends to be rapid due to the concentration of flow in fractures but can be highly variable over the local scale due to the heterogeneous system. In response to recharge pressures groundwater levels in Irish bedrock aquifers tend to respond rapidly when compared to, for example, UK hydrogeological settings. This suggests that there is a disparity between what is expected from the diffusivity values and observations of how groundwater levels in Irish bedrock aquifers respond to hydraulic stress such as rainfall events. It is noted that groundwater level response time and hydraulic stress propagation in an aquifer are not the same and do not necessarily happen at the same speed and timescale.

GSI REVIEW OF STREAMFLOW DEPLETION SOLUTIONS

Geological Survey Ireland (GSI) have reviewed a wide range of analytical, semi-analytical, blended and modelling solutions for streamflow depletion (summarised in Table 1). This paper presents selected results from the review and a tiered assessment framework (see Table 2)

[1] Regionally important karstified bedrock aquifer dominated by diffuse flow. For more information on GSI aquifer categories see GSI, 2017

which aims to facilitate the selection of appropriate methodologies for quantifying streamflow depletion.

Table 1: *Streamflow Depletion solutions which have been reviewed by Geological Survey Ireland. The table includes the setting and the information provided by each solution.*

Solution	Setting / Application	Provides information on:
Jenkins (1968)	Confined or unconfined aquifer	Stream Depletion Factor
Glover and Balmer (1954)	Confined or unconfined aquifer with differing representations of streams	Fraction of streamflow depletion as a function of groundwater abstraction rate
Hantush (1965)		
Hunt (1999)		
Ward and Lough (2011)	Semi-confined, leaky aquifer	As above and analysis of drawdown
Theis (1941)	Confined aquifer	Analysis of drawdown
Hantush-Jacob (1955)	Semi-confined, leaky aquifer	
Zipper (1999)	Blends analytical solutions with apportionment equations	Spatial and temporal distribution of streamflow depletion impact
Numerical Modelling (MODFLOW)	Complex settings; cumulative assessments	Streamflow depletion; spatial and temporal distribution; and apportionment between captured groundwater discharge and induced infiltration.

ASSUMPTIONS OF ANALYTICAL SOLUTIONS

Analytical solutions represent idealised aquifer conditions that make it possible to describe complex subsurface water flow and the propagation of hydraulic stresses. These solutions rely on several simplifying assumptions. Typically, aquifers are assumed to be homogeneous and isotropic with respect to hydraulic properties and to extend infinitely so that boundaries do not influence the response to pumping. Pumping is assumed to occur from a single well at a constant rate. When a stream boundary is included, the stream is assumed to be straight and infinitely long, with a constant stage. In many analytical solutions, the stream is also assumed to be fully hydraulically connected to the aquifer, meaning that changes in groundwater levels can directly influence streamflow.

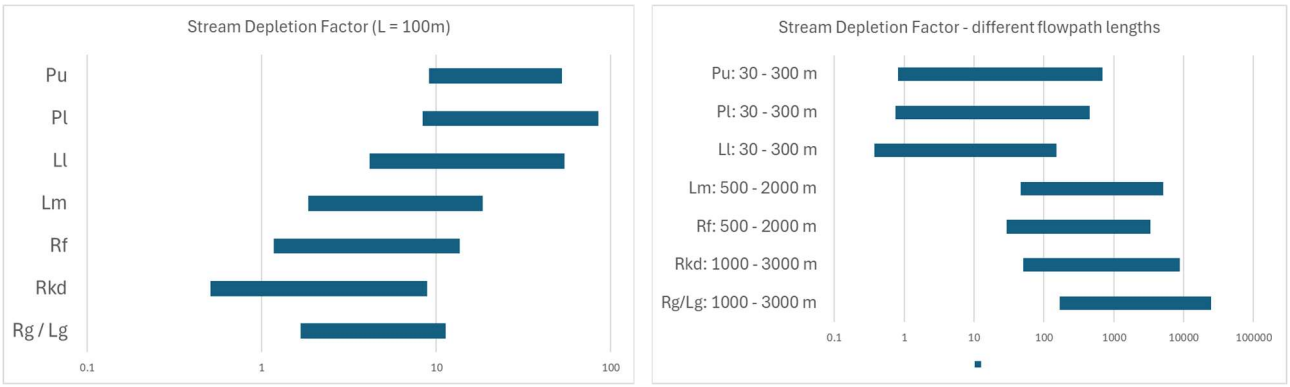

Figure 3: *Stream Depletion Factor (days) for different Irish aquifer types. Figure 3a assumes the groundwater abstraction is 100m from the stream; Figure 3b shows the likely range of Stream Depletion Factors (days) in Irish aquifer settings given the assumed flowpath lengths for different aquifer types.*

RESULTS FOR SELECTED ANALYTICAL SOLUTIONS

JENKINS (1968)

Jenkins developed the Stream Depletion Factor as a practical management tool. Stream Depletion Factor (SDF – not be confused with Streamflow Depletion SFD!) is defined as the squared distance from the well to the stream divided by Diffusivity (Jenkins, 1961). Jenkins showed that when pumping duration equals the SDF, streamflow depletion is approximately

28% of the pumping rate. Small SDF values indicate rapid stream response and early depletion, whereas large SDF values indicate delayed streamflow depletion impact.

Figure 3a shows that the Stream Depletion Factor for Irish aquifers range from <1 day (for Rkd aquifer) to almost 100 days (for Pl aquifer) when the distance between the groundwater abstraction and stream is set at 100m. When differing flow path lengths are assumed for the different aquifer types, Figure 3b shows that poorly productive aquifers have a range of Stream Depletion Factors up to almost 100 days and productive fractured and sand and gravel aquifers range of Stream Depletion Factors up to 25,000 days.

RESULTS FOR GLOVER, HUNT and WARD AND LOUGH

Figures 4 and 5 show the conceptual models for the Glover, Hunt and Ward and Lough solutions (known in this discussion as the Glover, Hunt and Ward and Lough solutions). Figure 6 shows a comparison of the streamflow depletion (calculated as a fraction of the groundwater abstraction rate) for these three solutions. The rows of graphs represent different Irish hydrogeological settings and the columns of graphs show increasing distance between the pumping well and the stream.

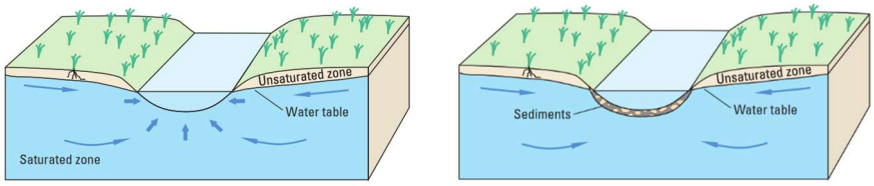

Figure 4a: *Glover and Balmer (1954) solution represents a stream with streambed and streambed sediments the same as the aquifer sediments.*
Figure 4b*: Hunt (1999) represents a stream with streambed and streambank sediments less permeable than the surrounding aquifer sediments. After Barlow and Leake (2012).*

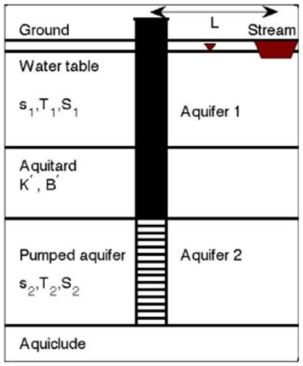

Figure 5: *Conceptual model for Ward and Lough soltion. After Ward and Lough (2011).*

Analyses were carried out for each Irish aquifer type individually. The results were sufficiently similar within the following groups for them to be considered together for the remaining analyses: poorly productive (Pu, Pl and Ll); productive fissured (here considered Rf, Rkd and Lm) and sand and gravel (Rg and Lg). Assessments were not carried out for Rkc aquifers as the use of simplified analytical solutions is not appropriate in any karst-conduit scenario (EPA, 2025).

Figure 6 shows that the Glover and Hunt solutions predict similarly high streamflow depletion rates particularly in the productive and sand and gravel aquifers. The impact of the streambed sediments present in the Hunt solution means results are very slightly delayed and lower in magnitude when compared to the Glover solution. The Ward and Lough solution predicts impacts which are more significantly delayed and lower in magnitude compared to the Hunt and Glover solutions in the three aquifer settings.

At 100m in all settings the depletion fraction reaches at least 80% which means that 80% of the pumping rate is sourced by inducing infiltration from the stream or intercepting groundwater flow which would have otherwise flowed into the stream. At 500 m Hunt and Glover models still predict depletion fraction over 80% but the Ward and Lough solution drops significantly to 30%, 70%, and 65% in Poorly Productive, Productive and Sand and gravel aquifers respectively. At 2000m Hunt and Glover solution shows depletion of 50%, 82% and

80% in Poorly Productive, Productive and Sand and gravel aquifers whereas Ward and Lough projects in all settings depletion fraction less than 20%.

As highlighted above the assumptions made for analytical solutions do not account for the heterogeneities of Irish aquifer systems. The greyed-out boxes in Figure 3 are an attempt to put limits on the solutions. For example, poorly productive aquifers are less likely to have kilometre scale flowpaths. Locally important sand and gravel aquifers tend to be limited in extent so to have a 2 km flowpath from an abstraction to a stream within a Lg is less likely – though it may be possible in a Rg aquifer.

DISCUSSION OF ANALYTICAL SOLUTIONS IN IRISH SETTINGS

There is noticeable lack of aquifer property data for Irish hydrogeological settings when compared to international data. This is particularly true for aquifer storage data (only 35 storage values are available in Kelly et al. (2015) across all aquifer types in unconfined settings). More aquifer property data are needed to refine the diffusivity values for Irish aquifers and to better understand groundwater level response times and hydraulic stress propagation in Irish aquifers and then in turn to understand streamflow depletion in Irish settings.

Caution should be exercised when applying analytical solutions for streamflow depletion in Irish hydrogeological settings, arising from two separate aspects:

- Fractured rock settings v porous media settings. Analytical solutions rely on a set of simplifying assumptions (discussed later in this paper) which generally do not hold true in Irish fractured rock settings. Central to the implementation of such models is the assumption that a Representative Elementary Volume (REV) can be defined, thereby allowing the fractured system to be treated as an equivalent porous medium (Cook, 2003; van Tonder et al., 2002). Validating this equivalence requires a robust conceptual understanding of the specific site settings to ensure that the scale of observation aligns with the theoretical requirements of porous flow equations.

- Scale. Analytical solutions for streamflow depletion and diffusivity were largely developed to describe aquifers and water catchments which are orders of magnitude larger than those in Ireland. Excluding a handful of settings (e.g. the Burren or the Curragh) a person (or abstraction) in Ireland is almost always within 2 km of a watercourse. This disparity in scale means the analytical solutions available may not be transferable or applicable to the Irish hydrogeological setting.

ZIPPER METHODOLOGY

Zipper and colleagues published several papers (Zipper et al., 2019, 2021; Li et al., 2020) have published several papers on how to estimate streamflow depletion by blending analytical solutions with apportionment equations, which are responsible for distributing streamflow impacts across river segments in a catchment. A poster in this conference provides an overview of this approach including an Irish case study highlighting the possible spatial and temporal outputs. A more detailed discussion can be found in the original paper (Zipper, 2019).

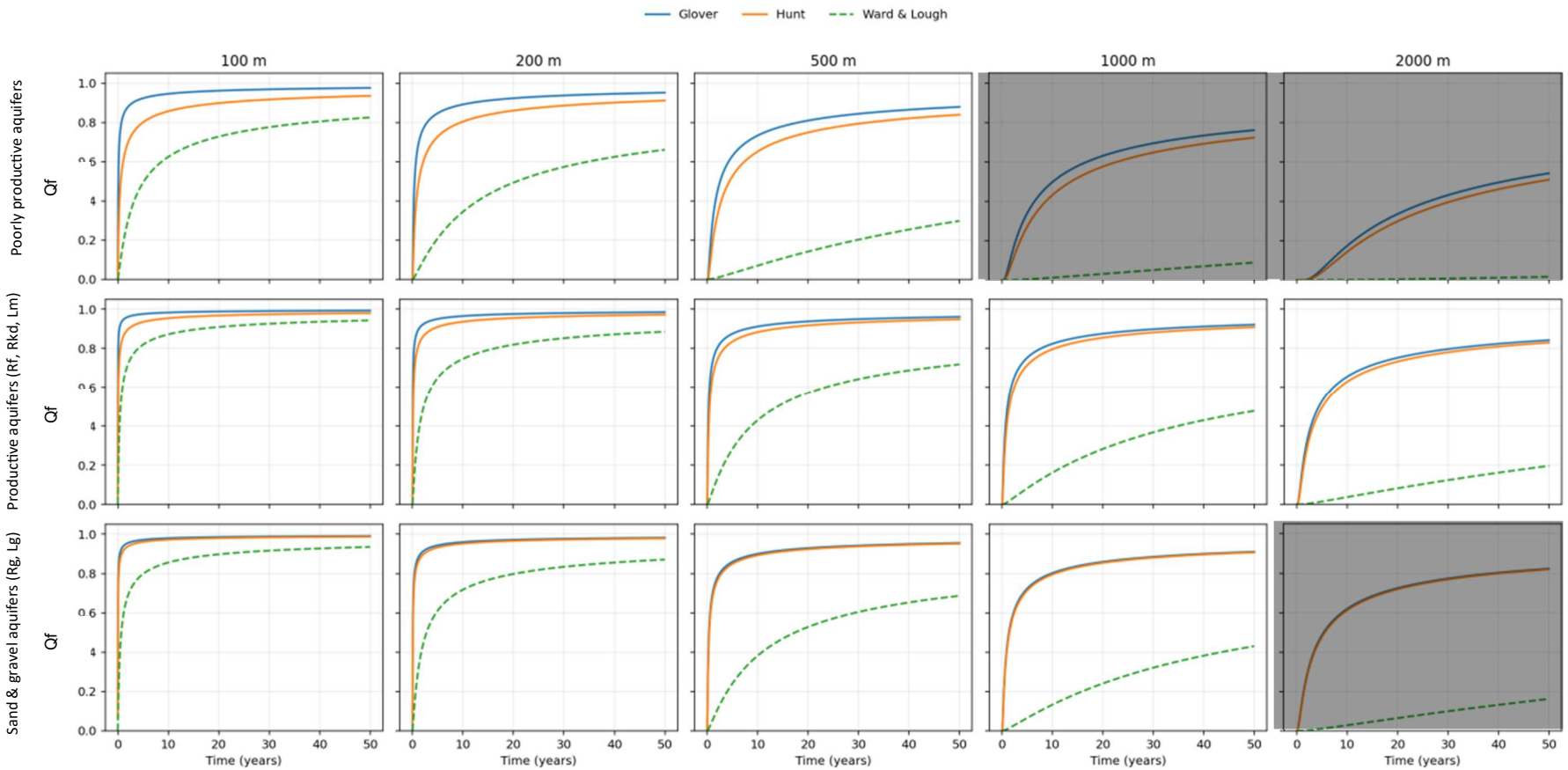

Figure 6: *A comparison of streamflow depletion shown as Qf a fraction of the groundwater abstraction rate for three analytical solutions: Glover (shown in blue); Hunt (shown in orange) and Ward and Lough (shown in dashed green). The rows of graphs represent different Irish hydrogeological settings and the columns of graphs show increasing distance between the pumping well and the stream. Greyed out panels are explained in the text.*

Table 2: *GSI's tiered framework for assessing streamflow depltion in Irish hydrogeological settings.*

Question	Approach	Tools	Application / Settings
Is it necessary to calculate streamflow depletion?	Assume SFD= 100% of abstraction rate. (Current assumption in EPA's QUBE model)	None	Initial conservative screening. If the EPA's River Waterbodies test's Hydrological Limit is not exceeded, then no further investigation required.
What is the magnitude of streamflow depletion from a single abstraction?	Select a suitable analytical solution depending on hydrogeological setting:	Glover & Balmer (1954)	Simple setting; no streambed sediments (Figure 4a)
		Hunt (1999)	Simple setting; with streambed sediments (Figure 4b)
		Ward & Lough (2011)	Two-layer leaky aquifer (Figure 5)
What is the scale and timing of streamflow depletion?	Calculation of Stream Depletion Factor (SDF)	Jenkins (1968)	Initial screening to understand the timing and magnitude of the stream response.
How will the drawdowns evolve around the abstraction? What is the extent of the cone of depression?	Select a suitable analytical solution depending on hydrogeological setting:	Theis (1941)	Confined settings
		Hantush & Jacob (1955)	Leaky aquifer settings
		Ward and Lough (2011)	Two-layer leaky aquifer (Figure 5)
What stream segments will be most impacted by the abstraction? How will the streamflow depletion impact the Q95 (or other metric) of the stream over time?	Combine analytical solutions listed above and apportionment equation to distribute streamflow depletion impact.	Zipper (2019) and Streamflow depletion RStudio package (streamDepletr)	Requires selection of analytical solution depending on hydrogeological setting e.g. Glover & Balmer (1954); Hunt (1999) or Ward & Lough (2011)
What is the magnitude of streamflow depletion from multiple abstractions in a catchment?	Select a suitable solution depending on level of detail required; as well as data and expertise available:	Combination of outputs from analytical models	Simple settings
		Zipper (2021)	Unconfined/confined settings
		Numerical modelling (e.g. MODFLOW)	Complex/ highly heterogenous settings
What is the magnitude and timing of streamflow depletion in a complex hydrogeological setting?	This approach can be used to identifying timing and magnitude of streamflow depletion.	Numerical Modelling (e.g. MODFLOW)	For example, more than one aquifer type, anisotropy, karst settings, impact of thick subsoils etc
What is the proportion of captured groundwater discharge compared to induced infiltration?	Separating captured discharge vs. induced infiltration	Numerical Modelling (e.g. MODFLOW)	Essential for water quality and nutrient loading assessments

GSI FRAMEWORK FOR ASSESSMENT OF STREAMFLOW DEPLETION

Table 2 presents GSI's tiered assessment framework which aims to facilitate the selection of appropriate methodologies for quantifying streamflow depletion based on the specific settings and objectives of a water management query. It ranges from a conservative initial screening, which assumes depletion equals 100% of the groundwater abstraction rate, to the use of analytical solutions (e.g. Glover, Hunt, or Ward and Lough) for determining the magnitude and timing of single abstractions in simpler settings. For more sophisticated requirements (such as assessing multiple abstractions, evaluating complex fractured or karst hydrogeology, or distinguishing between captured discharge and induced infiltration) the framework directs practitioners toward blended analytical packages (e.g. Zipper 2019, 2021) or numerical modelling (e.g. MODFLOW). As one progresses through the tiers of this framework, the outputs become more appropriate for complex settings but the associated requirements for data, time and technical expertise also significantly increase.

CONCLUSIONS

Understanding streamflow depletion in Irish hydrogeological settings has become increasingly important following the introduction of the new Water Environment (Abstractions and Associated Impoundments) Act 2022. Accurate quantification of streamflow depletion is critical component of water resource management and the protection of aquatic ecosystems.

GSI conducted a review of commonly used approaches to assess streamflow depletion. Results from selected analytical solutions (Hunt, Glover, and Ward and Lough solutions) are presented in this paper. They indicate that predicted streamflow depletion in Irish settings often represents a significant fraction of the abstraction rate. However, caution is required when applying these analytical solutions in Irish settings. Their underlying assumptions do not account for the heterogeneities in Irish fractured rock settings, potentially leading to inaccurate impact assessments.

GSI present a tiered assessment framework which aims to facilitate the selection of appropriate methodologies for quantifying streamflow depletion based on the specific settings and objectives of a water management query (Table 2).

To improve the reliability of SFD estimates, it is essential that more aquifer property data, particularly storage data, is gathered. Further work is recommended to evaluate the use of MODFLOW numerical modelling, which would provide a more nuanced understanding of depletion in fractured rock environments and allow for a robust comparison against the analytical solutions.

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COUPLED MONITORING AND MODELLING IN A GLACIOFLUVIAL AQUIFER: HYDROGEOLOGICAL PROBLEM-SOLVING FOR FUTURE WATER SUPPLY RESILIENCE

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ABSTRACT

Growing interest in developing groundwater resources for public water supply has highlighted the need for robust methods to characterise aquifer behaviour and understand groundwater–surface water interactions. The Lough Fea Sand and Gravel Aquifer, which feeds Anney's Well Spring in County Tyrone, represents a significant prospective groundwater source where understanding system dynamics is essential for assessing its potential contribution to regional supply schemes.

This study applies an integrated suite of monitoring and modelling techniques to investigate recharge processes, aquifer throughflow, and spring discharge in this glaciofluvial system. Methods included monthly dilution-gauging of spring discharge, groundwater-level monitoring, groundwater-flow mapping, recharge estimation using the Water Table Fluctuation and infiltration-coefficient approaches and lumped conceptual modelling using AquiMod2.

Outputs from these methods aligned closely, providing a coherent conceptual model that identifies Anney's Well Spring as the primary discharge point and demonstrates strong hydraulic connectivity across the aquifer. The consistency between independent approaches increases confidence in the interpretation of recharge dynamics, flow pathways, and aquifer response to hydrological variability.

The findings demonstrate the value of combining monitoring and lumped modelling techniques to support groundwater resource assessments, evaluate the potential impacts of abstraction, and strengthen evidence for sustainable groundwater development. The approach is transferable to similar aquifers across Ireland.

Key words: *spring, sand, gravel, catchment, flow, resilience, monitoring, water, glaciofluvial, modelling, Aquimod*

INTRODUCTION

Increasing demand variability, climate extremes and environmental-flow constraints are placing new emphasis on conjunctive water management. In Northern Ireland—where public supply is predominantly surface-water based—strategically located sand and gravel aquifers offer opportunities to enhance resilience during peak-demand and dry-weather periods.

The Lough Fea Sand and Gravel Aquifer feeds Anney's Well Spring, an important headwater source to the Lissan Water in the Ballinderry catchment. Although the aquifer spans both the Moyola and Ballinderry catchments, this investigation focuses on the Ballinderry side, where the aquifer lies close to existing infrastructure and offers potential as a low-carbon supplementary source in an already supply-constrained zone.

Developing this source requires evidence of long-term sustainability and minimal impact on sensitive downgradient receptors. This study demonstrates how coupled monitoring and numerical modelling can provide defensible hydrogeological understanding to support future groundwater development.

HYDROGEOLOGICAL SETTING

Anney's Well Spring drains the Lough Fea Sand and Gravel Aquifer. Five exploratory and monitoring boreholes indicate 8–10 m of sand and gravel with groundwater levels near the surface as shown in ***Figure 6***. Artesian conditions in some boreholes suggest partial confinement linked to lower-permeability glaciolacustrine units. Pumping tests yielded transmissivities of 1,700–4,500 m²/d and specific yield ~0.1.

The spring's topographical catchment is estimated at 2.414 km².

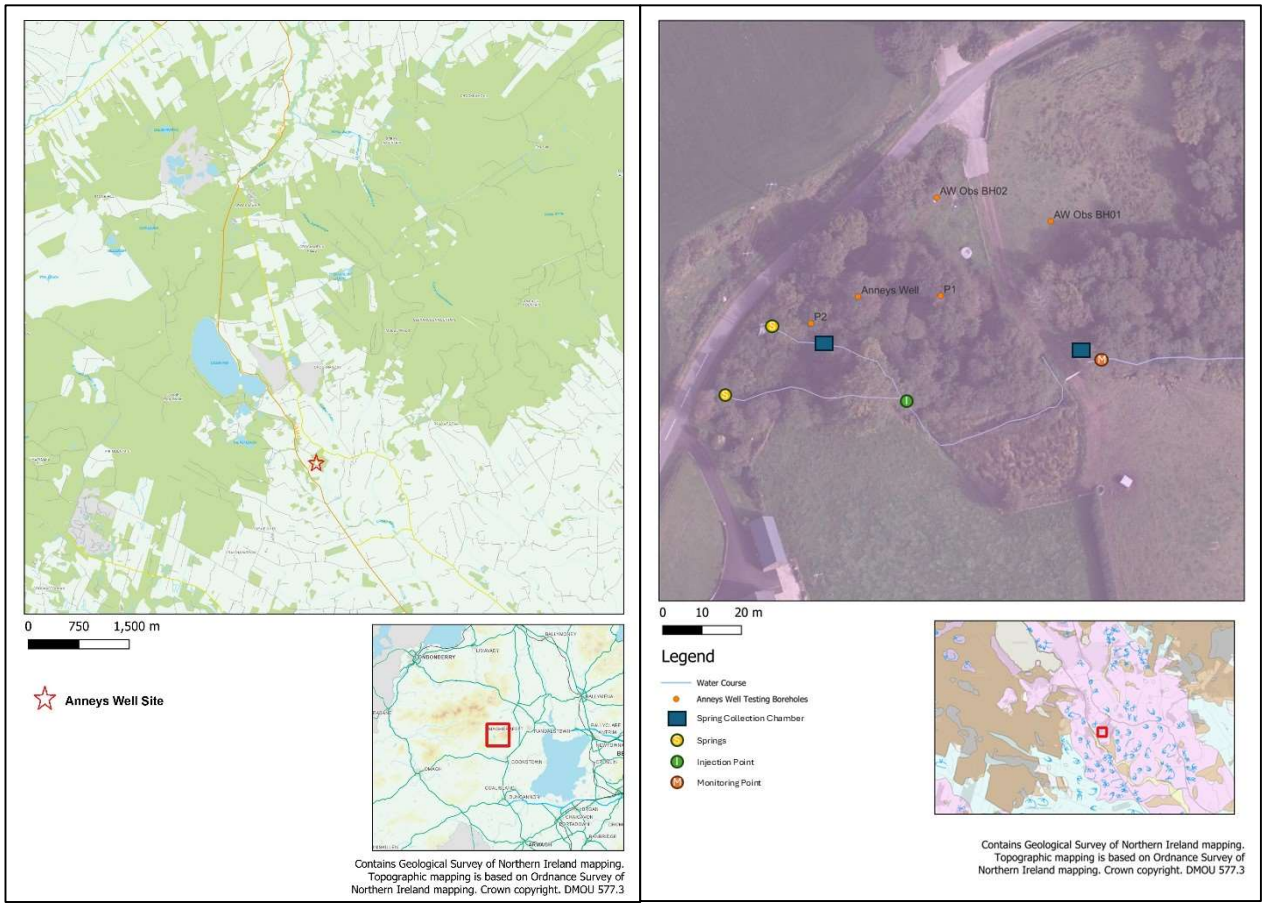


Figure 6*: Lough Fea Sand and Gravel aquifer and Anney's well spring site*

MONITORING AND DATA

High-quality field data remain essential despite advances in modelling and computation. The study aimed to quantify sustainable abstraction without adversely affecting spring discharge or flows in the Lissan Water.

Monitoring comprised:

- Continuous groundwater-level logging to capture recharge and seasonal trends.
- Monthly salt-dilution spring gauging to define the spring discharge regime and derive a Flow Duration Curve (FDC).
- Low-flow river survey to validate baseflow inputs.

- Meteorological data (rainfall, PET) from Lough Fea Met Station for recharge estimation and model forcing.

METHODS

A combined field-measurement and numerical-modelling workflow was used to quantify recharge, characterise spring behaviour and evaluate abstraction options.

RECHARGE ESTIMATION

- Infiltration-coefficient method: Effective rainfall weighted by mapped superficial geology (sand/gravel vs peat) (Misstear and Brown, 2009a).
- WTF method: Recharge inferred from departures from groundwater recession using literature-based specific yield (Healy and Cook, 2002).

SPRING FLOW CHARACTERISATION

Salt-dilution gauging (Kilpatrick & Cobb, 1985) was paired with groundwater levels to develop an empirical groundwater–spring response model.

LUMPED MODELLING

A 1-D AquiMod 2 bucket model, as demonstrated in ***Figure 7*** (Mackay et al., 2022) was calibrated to observed groundwater levels using rainfall and FAO-56 PET (Allen et al., 1998). Once calibrated, the model reconstructed historic groundwater behaviour and simulated the throughflow feeding Anney's Well.

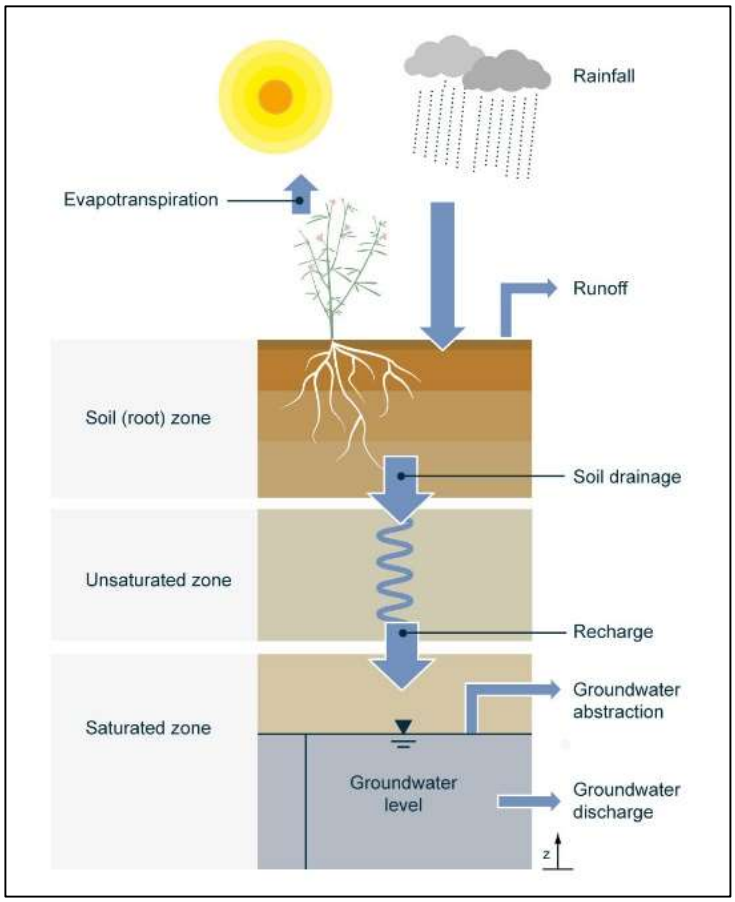


***Figure 7**: Generalised structure of AquiMod. BGS © UKRI.*

ABSTRACTION SCENARIO TESTING

Two operating strategies were evaluated:

1. Continuous pumping: 0.5–3 MLD
2. Seasonal abstraction (Apr–Sep)

Impacts were assessed relative to Q95 and groundwater-level drawdown.

RESULTS

RECHARGE ESTIMATES

Long-term climate data from the Lough Fea Met Station (1990–2024) show an average effective rainfall of 938 mm/year.

- Infiltration-coefficient method - 0.8–0.9 for the glaciofluvial sand-and-gravel deposits and 0.01–0.5 for areas of peat cover (Hunter Williams et al., 2013):

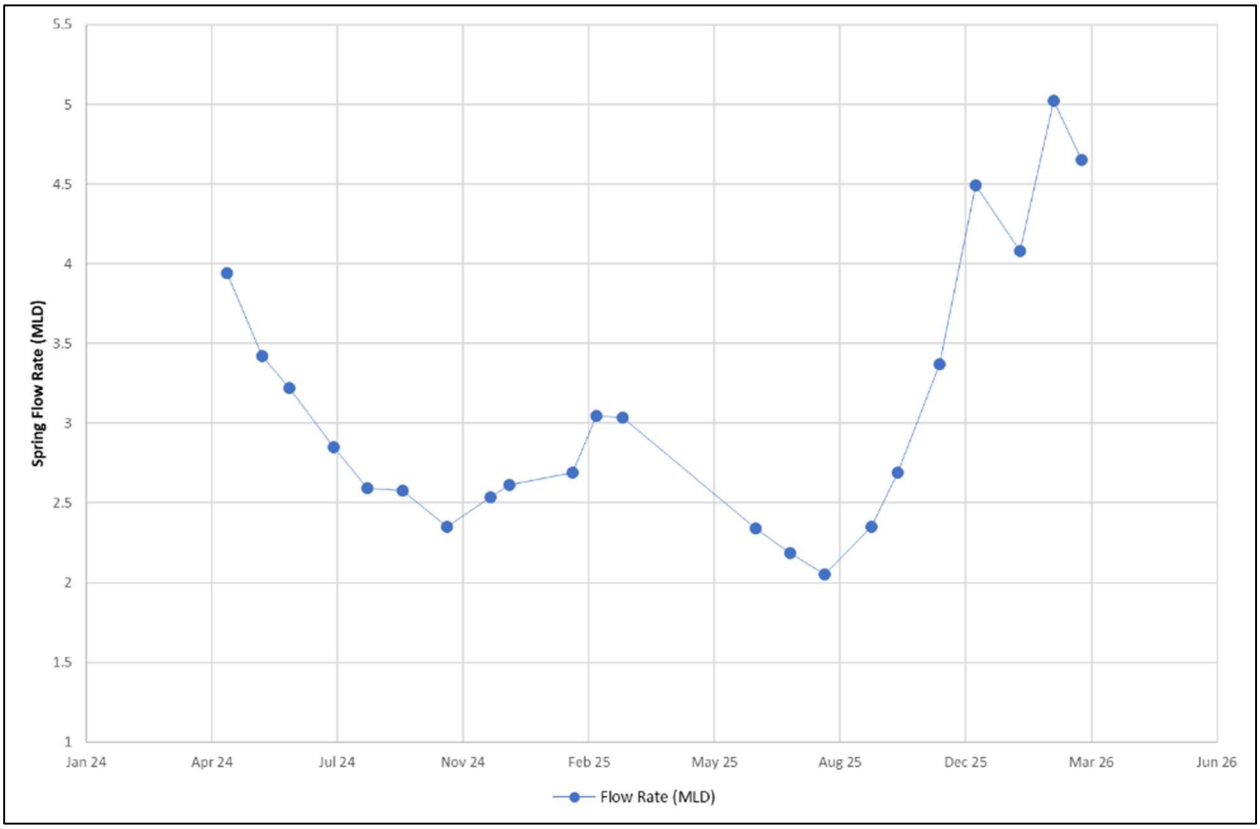
  Recharge = 516–756 mm/yr (≈ 3.4–5 MLD).

- WTF method - specific yield values of 0.21–0.28 (Morris & Johnson, 1967):
  Recharge = 765–1277 mm/yr (≈ 5–8 MLD).

SPRING FLOW CHARACTERISATION

Spring discharge ranged 2–5 MLD (

Figure 8). Groundwater levels and spring flow showed a strong relationship as shown in ***Figure***



9 (power-law, $R^2 = 0.95$).

Figure 8: *Temporal Spring flow measurements*

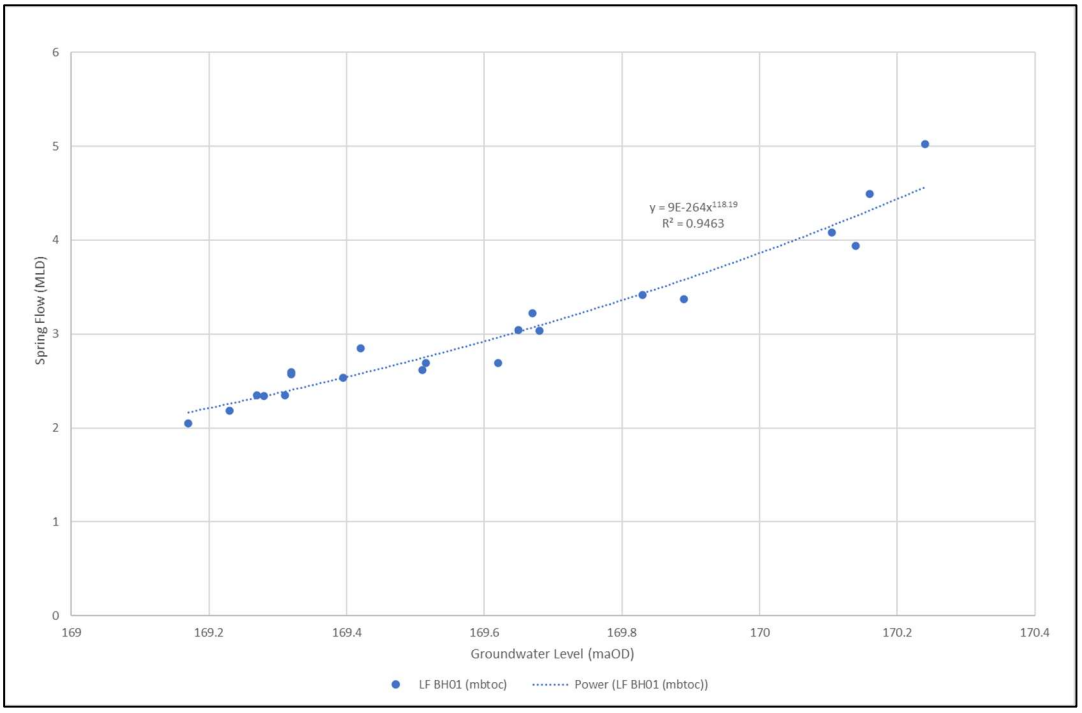


Figure 9: *Spring flow and groundwater level correlation*

LUMPED MODELLING RESULTS

AquiMod 2 reproduced groundwater levels well as shown in ***Figure 10*** (NSE = 0.98). Simulated throughflows feeding the spring were 2.5–4.5 MLD.

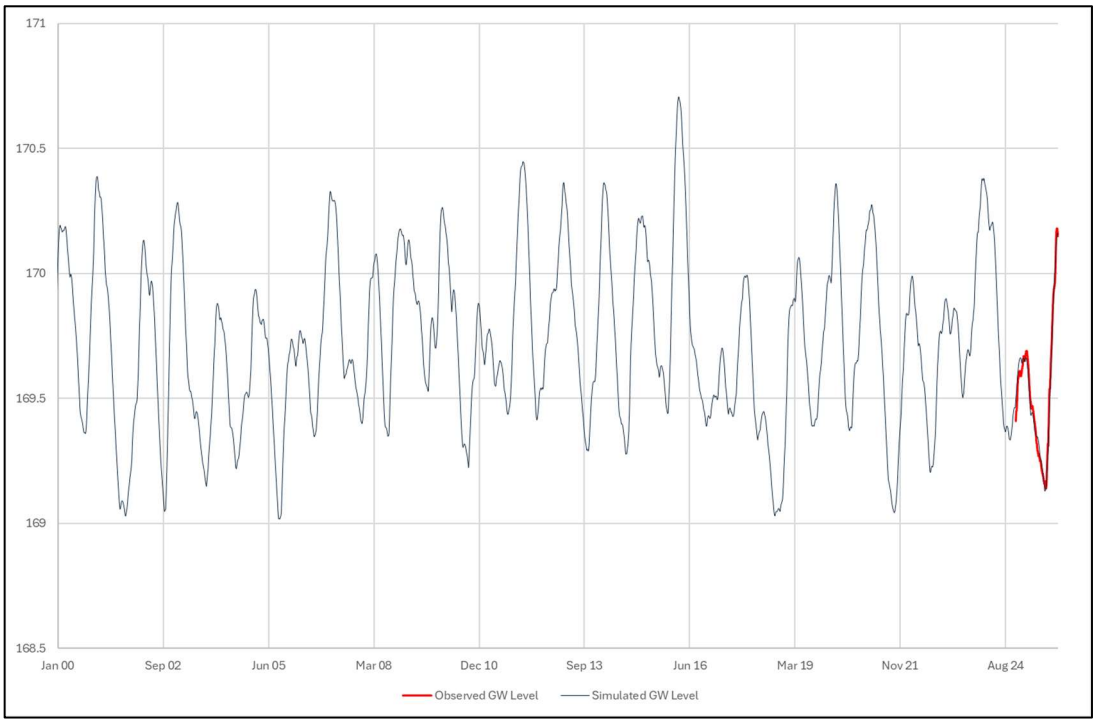


Figure 10: *Observed and simulated groundwater levels from 2000 – 2025*

Applying the groundwater–spring response model, shown in ***Figure 9***, yielded a long-term spring flow distribution curve (

Figure 11) with Q95 = 2.05 MLD, and total annual flow of 1,166 ML, equivalent to 3.2 MLD or 484 mm/yr of recharge over the 2.414 km² catchment.

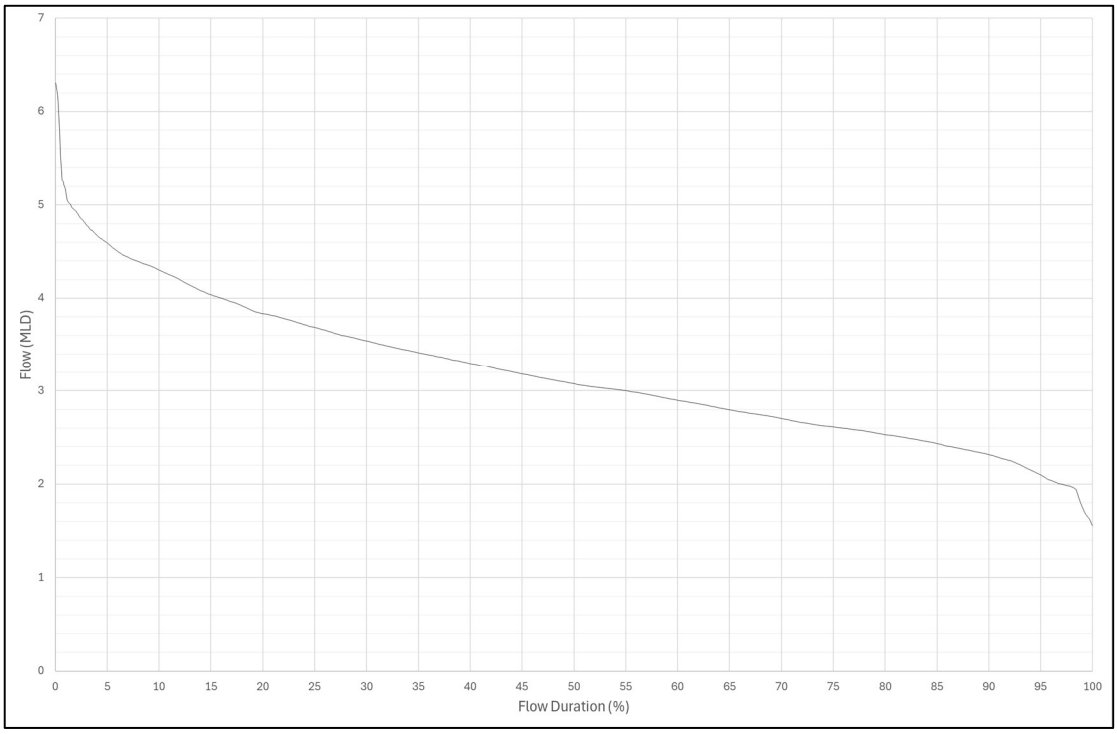


Figure 11: *Spring flow duration curve*

ABSTRACTION SCENARIO TESTING

A precautionary abstraction limit of 10% of Q95 (~0.21 MLD) for ecologically sensitive catchments applies when flows approach Q95. Above Q95, greater abstraction is possible.

Seasonal abstraction performed best:

- Continuous 1 MLD abstraction feasible ~67% of the year.
- Seasonal abstraction resulted in fewer low-flow breaches and full winter groundwater recovery as shown below in ***Figure 12***.
- Figure 7 below shows how a variable abstraction regime can be proposed based on the derived spring-flow duration curve.

DISCUSSION

RECHARGE ESTIMATES

Recharge estimates converge around a realistic effective recharge of ~484–636 mm/yr (≈ 3.2–4.2 MLD), supported by infiltration-based, modelled and spring-derived values. WTF values represent upper-bound gross recharge. Table X.

The spring flow-duration curve estimate—484 mm/yr (3.2 MLD)—offers the most reliable measure of effective recharge to the spring. If a minimum spring discharge equivalent to Q95 (~2 MLD) is to be maintained, a seasonal abstraction of approximately 1.2 MLD is reasonable.

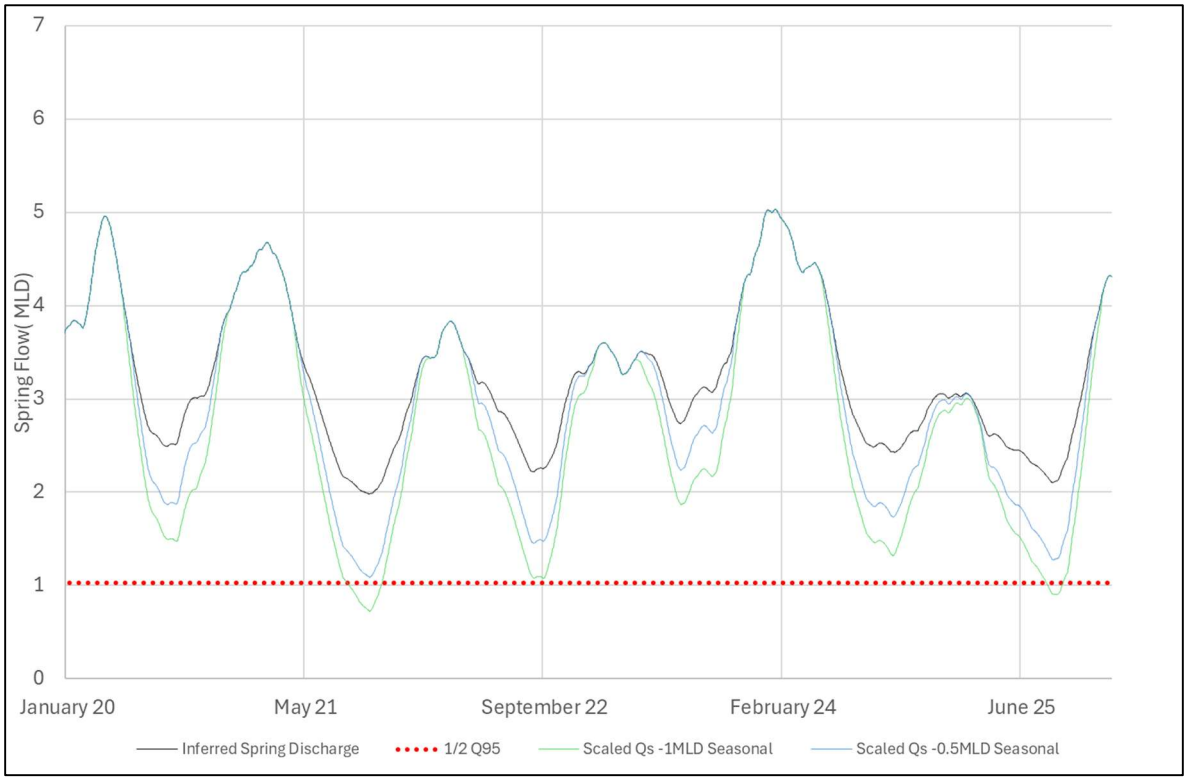


Figure 12: *Modelled seasonal abstraction scenarios influence on groundwater levels*

Table 3: *Groundwater recharge estimates summary*

Method	Flow (MLD)	Equivalent Recharge (mm/year)
Flow duration curve-derived spring discharge	3.2 MLD	~ 484 mm/yr
Infiltration-coefficient (IC) average *(mid-point of 3.4–5.0 MLD)*	4.2 MLD	~ 636 mm/yr
WTF method (average)	6.5 MLD	~ 985 mm/yr
AquiMod-2 throughflow (average) *(mid-point of 2.5–4.5 MLD)*	3.5 MLD	~ 530 mm/yr

GROUNDWATER–SPRING CONNECTIVITY

Strong correlation between groundwater levels and spring discharge confirms that Anney's Well is a single, focused outlet with limited intermediate storage. This may be controlled by internal relatively impermeable layering within the glaciofluvial outwash deposits. This simplifies abstraction impact assessment and could enable future operational monitoring of groundwater levels as a correlative of spring flow.

MODEL PERFORMANCE

AquiMod 2 aligns with observed discharge and independent recharge estimates, demonstrating its suitability for simulating aquifer behaviour despite its simplicity. By reliably replicating and forecasting groundwater levels, the model offers wide practical value for hydrogeological work across Ireland.

FLOW DURATION CURVE

The FDC provides a transparent basis for defining low-flow thresholds and reconciling groundwater abstraction with downstream ecological protection.

ABSTRACTION FEASIBILITY

Seasonal abstraction offers the best balance between supply and environmental protection, enabling ~1 MLD abstraction while maintaining Q95 flows and allowing winter recovery.

CONCLUSIONS

- Monitoring and modelling converge on an effective recharge of ~3.2 MLD, confirming a resilient glaciofluvial aquifer system.
- Strong groundwater–spring connectivity enables confident prediction of abstraction impacts.
- AquiMod 2 effectively simulates system behaviour and supports resource-management decisions.
- Seasonal abstraction of ~1 MLD is sustainable while protecting Q95 low flows.
- The coupled approach provides a practical framework for future groundwater development in similar aquifers.

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SESSION III

ECOHYDROLOGICAL MAPPING OF IRISH RAISED BOGS FROM SATELLITE MULTISPECTRAL AND GROUND MOTION DATA VIA MACHINE LEARNING

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ABSTRACT

Assessing peatland condition at national scale is key to meeting Irish and European environmental ambitions. Earth Observation satellites deliver information on peatland ecology and hydrology, which, if automated via machine learning, could be scaled towards national peatland condition mapping. Here we investigate how a combination of multispectral satellite imagery with ground surface displacement data from satellite InSAR enhances such mapping. Using pre-existing ground truth mapping, Sentinel-2 multispectral images and European Ground Motion Service data, we trained a range of machine learning models based on Artificial Neural Networks to automatically classify and map ecological communities on 34 temperate raised bogs in Ireland. The results show that using multispectral imagery and ground motion data together produces a statistically significant improvement in machine learning performance over using multispectral imagery alone. Moreover, the use of ground motion time-series alone produces a model performance almost as good as the use of multispectral data alone. A systematic variation in the average pattern of ground motion through time within the different peatland ecological communities is observed and is proposed to underpin the success of machine learning models. Such variation likely reflects distinct patterns of groundwater level variation in both space and time.

Key words: *Machine Learning, Earth Observation, Sentinel-2, European Ground Motion Service, Peatland Condition, Peatland Ecology, Peatland Hydrology*

INTRODUCTION

Peatlands are terrestrial wetland ecosystems characterised by high water tables, anoxic soil conditions and the long-term accumulation of organic matter as peat. In good condition, they provide essential ecosystem services, such as carbon storage, water filtering, and habitats for specially adapted biodiversity. Approximately 16,800 km^2 (24%) of the Republic of Ireland is covered by peat soils (Gilet et al., 2024), yet some 80% are degraded (Wilson et al., 2013. Environmental initiatives such as Ireland's National Climate Action Plan and the European Union (EU) Green Deal (IPCC, 2024; European Commission, 2026) envisage conservation, restoration or rewetting of vast peatlands areas. Consequently, peatland condition assessment at national scale and at monthly to annual frequency is required to identify pressures (e.g. cutting, erosion, fires and landslides), to prioritise areas for restoration or rewetting, and to validate restoration effectiveness.

Peatland ecology and hydrogeological behaviour are interlinked proxies of peatland condition (Wilson et al., 2013); Kelly and Schouten, 2002). At raised and blanket bogs, good condition is indicated by dominance of peat-forming vegetation such as *sphagnum moss*. Bad condition is indicated by domination of vascular plants such as heather and/or by areas of exposed peat. Sphagnum moss growth and CO_2 sequestration occur in temperate peatlands where mean annual groundwater tables are maintained at 5-15 cm below ground level (Evans et al., 2021). Changes in ground water level at peatlands are known to drive changes in ground surface

level. A seasonal rise and fall of the peatland ground surface, known as '*bog breathing' or 'bog surface oscillation',* is linked to seasonal change of water table depth, and it is considered by some to be a sign of good ecohydrological condition and potentially of restoration success (Howie and Hebda, 2018).

The traditional approach to assess peatland condition is via in-situ ecological surveying and hydro(geo)logical measurements, complemented by manual analysis of optical aerial imagery (Fernandez et al., 2014). This leads to precise information, but it is typically point-wise in space and highly time consuming. Prioritisation of resources leads to greater volumes of information in certain areas whilst others remain unexplored, especially where hard-to-access and/or remote. In-situ monitoring efforts are also commonly time limited, and so may not satisfy the spatiotemporal requirements of national-scale peatland condition assessment. Earth observation from satellite-based sensors can, on the other hand, yield long-term, freely available datasets that function as proxies for peatland ecohydrological condition across all of Ireland.

The Sentinel-1 Synthetic Aperture Radar (SAR) (Potin et al., 2019) and Sentinel-2 multispectral (Gascon et al., 2014) satellites of the EU Copernicus program both acquire data at moderate spatial resolution (5-60 m per pixel side) on a near-weekly basis. Sentinel-2 passively captures radiation emitted or reflected from the Earth as ultraviolet, visible or infrared light, analysis of which has long been fundamental to discerning land cover types and vegetation health. Sentinel-1 emits pulses of C-band microwaves and records their backscattered amplitude and phase. An advantage of SAR is that microwaves penetrate clouds. Thus, unlike for multispectral data, a regular and dense time-series of SAR measurements can be made in humid temperate climates such as in Ireland. Moreover, mm-precision estimates of ground surface motion can be derived from interferometric processing of SAR phase data (InSAR). Recent work led by UCD has validated InSAR-derived ground motions with similarly precise in-situ measurements at raised bogs in Britain and has linked these motions to water table fluctuation (Hyrsiewicz et al., 2024).

In this study, we tested whether InSAR-derived ground motion data can be used to map raised bog ecology via machine learning. Given a baseline machine learning model previously trained to infer vegetation communities from multispectral data only (Grappiolo et al., 2024; Ferch et al., 2026), we show a near equivalent performance in models trained only on ground motion time series and a significantly improved performance in models trained on both multispectral imagery and ground motion timeseries. This finding indicates that patterns of ground motion at peatlands are closely tied to peatland ecological condition via hydrogeological controls.

DATA AND METHODS

STUDY SITES AND GROUNDTRUTH DATA

Our investigation is centred on 34 Irish raised bogs (Figure 1A) for which recently updated maps of vegetation communities (*ecotopes*) (Fernandez et al., 2014) were available from the Irish National Parks and Wildlife Service (NPWS) (Figure 1B). The total studied bog area is 5881 ha.

We focus here on seven ecotopes identified by traditional ecological mapping. The *Central* (93 ha)*, Sub-central* (557 ha)*,* and *Active flush* (78 ha) ecotopes are moss-rich and correspond to active raised bog habitats, where conditions are healthy and promote active peat accumulation. The *Sub-marginal* (3045 ha)*, Marginal* (1496 ha)*, Inactive flush* (312 ha), and *Facebank* (170 ha) ecotopes correspond to degraded raised bog habitats. Other land cover classes of significance within the ground truth dataset include *Bog Woodland* (10 ha) and *WD4 Conifer plantation* (66 ha), which refer to afforested peatland areas, while the class *Coillte LIFE restoration area* (45 ha) refers to cutover bog areas subjected to past cutting and drainage and now under restoration. Only one ecotope or other land cover class is assigned to any one location within a raised bog.

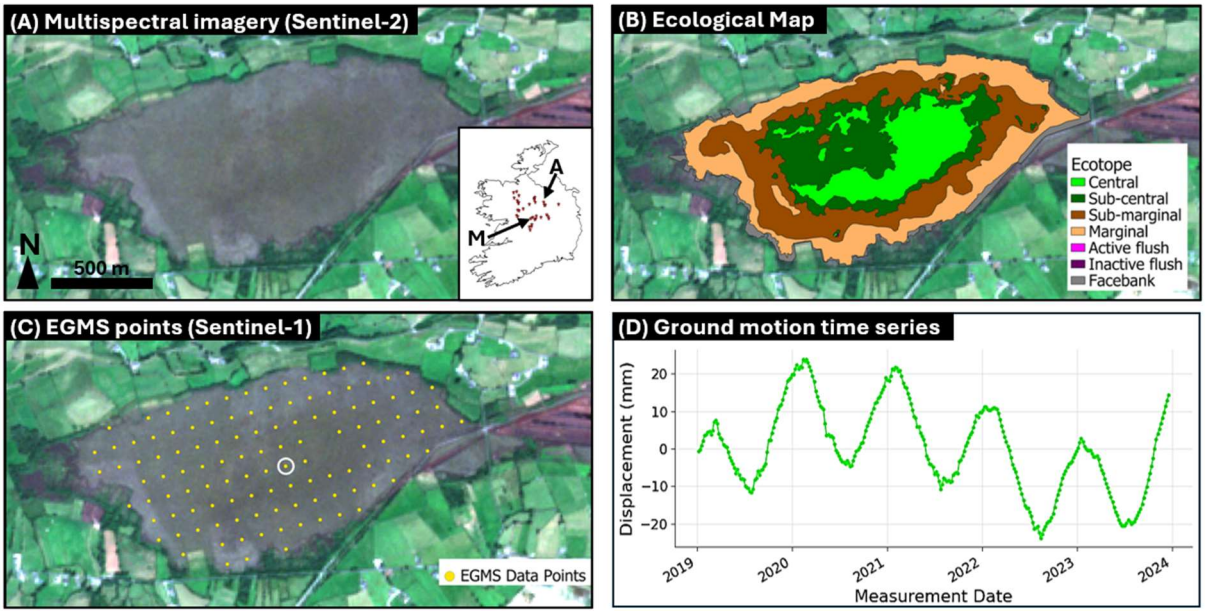

Figure 1: *Overview of datasets used in this study. (A) Example of a cloud-free Sentinel-2 L2A multispectral image (red-green-blue bands; natural colour) aquired in August 2022 over Mongan bog Co. Offaly. Inset shows the location of the 34 Irish bogs considered in our study (red stars), with arrows pointing to Mongan and Ardagullion bogs. (B) Example of ground truth ecotope map from NPWS. (C) Example of 100m gridding of Level 3 EGMS point locations (yellow points) (D) Example of EGMS timeseries data for the white encircled point in part C.*

EARTH OBSERVATION DATA

For each bog we retrieved a cloud-free, Sentinel-2 L2A multispectral image captured on 13th August 2022 (Figure 1A). For each image pixel, reflectance values in 11 wavelength bands were obtained (Table 1). Also, five commonly-used spectral indices (NDVI, mSAVI, NDMI, GCI, and NDWI) were made by normalising reflectance values of one or more bands to those of others.

Table 1: *Summary of Sentinel-2 Multispectral Imager (MSI) bands used in this study*

Band	Wavelength (nm)	Band Reference Name	Spatial resolution (m)
1	443.9	Coastal Aerosol	60
2	496.6	Blue	10
3	560	Green	10
4	664.5	Red	10
5	703.9	Red Edge 1	20
6	740.2	Red Edge 2	20
7	782.5	Red Edge 3	20
8	835.1	Near Infrared	10
8a	864.8	Red Edge 4	20
11	1613.7	Short Wave Infrared 1	20
12	2202.4	Short Wave Infrared 2	20

Peat surface motion data for each bog were obtained from the European Ground Motion Service (EGMS) (Crosetto et al., 2021). Derived from Sentinel-1- InSAR, the EGMS is a point-based, publicly available repository of ground displacement through time at millimetre precision across most of Europe. Within the 34 Irish raised bogs, we retrieved 5,246 EGMS Ortho (Level 3) observation points of vertical surface displacement. Points are gridded at 100 m spacing (Figure 1C). Each point represents a displacement time-series dating from 7th January 2019 to 18th December 2023 with a six-day temporal spacing of displacement

measurements (302 measurements per point) (Figure 1D*)*. For each point, we considered in our analysis the full timeseries of vertical displacement, as well the following seven EGMS 'trend' summary variables: velocity (mean and std. dev.), acceleration (mean and std.), seasonality (mean and std. dev.), and Root Mean Square Error (RMSE).

MACHINE LEARNING MODELS

We tackled the ecotope mapping problem via supervised machine learning and classification. Based on our previous work (Grappiolo et al., 2024), we relied on Artificial Neural Networks (ANNs). We considered seven ANNs, all of which share the same architecture but differ in the input layer. This enables assessment of the contribution of different input features (e.g. with or without EGMS timeseries) to the model's inference performance (Table 2)

Table 2: *Overview of the Architectures of the Artificial Neural Network Models. The model names refer to the input data used in each architecture, for example model "S2" takes only Sentinel-2 data at a given point as input, whereas as model "S2_timeseries" takes both Sentinel-2 data and EGMS displacment time series data at a given point as input. "Trend features" refers to summary variables of the EGMS time series (see main text).*

ANN name	***Sentinel-2 L2A and veg. indices***	***EGMS data***		***Input layer size***
		Trend features	***Timeseries***	
S2	✓	✗	✗	16
trend	✗	✓	✗	7
timeseries	✗	✗	✓	302
full_egms	✗	✓	✓	309
S2_trend	✓	✓	✗	23
S2_timeseries	✓	✗	✓	318
S2_full_egms	✓	✓	✓	325

The seven neural networks have the following hidden topology: [64, 32, 10]. Each layer is subject to L2 regularisation, batch normalisation and dropout (30%). The Swish activation function is used for all neurons except for the output layer, for which Softmax is used. Gaussian noise is introduced in the first layer (mean = 0, standard deviation = 0.05). Training is performed by means of Adam (learning rate $10e^{-3}$) and categorical cross-entropy loss with label smoothing (0.05) and early stopping (patience 30 epochs). Mini batch size is 64.

EXPERIMENTAL PROTOCOL

To assess the performance of the seven model architectures, a strict 10-fold cross-validation experimental setup is implemented. This leads to 70 trained models (10 per architecture). The full dataset of 5,246 points is subdivided into training (3,777 points; 72%), validation (944 points; 18%) and testing (525 points; 10%). Each train/validation/test set of each fold underwent a standard scaling normalisation process prior to input to the model. Each model is trained on the same dataset in all folds.

Model performance is quantified in terms of the average and standard deviation of weighted F1 scores, as registered across the 10 folds run for each of the seven ANN architectures. Additionally, we compare the F1 score to that obtained by a random classifier model, which samples one out of eight possible ecotopes with probabilities proportional to their distribution in the dataset. To check for statistical significance of any improvement in model performance, we calculated p-values resulting from two Student's t-tests. The first test is based on the null hypothesis that models perform equally well to the model considering multispectral data only (*S2*). The second test is based on the null hypothesis that the models perform equally well to the model considering both multispectral and all EGMS data *(S2_full_egms*). All t-tests are paired, two-tailed, and have nine degrees of freedom.

RESULTS AND DISCUSSION

The best performing model architecture (*S2_full_egms)* is the one accepting all 325 input features from both multispectral reflectance data and ground surface motion data (***Table 3***). The *S2_full_egms* model architecture achieved an average weighted F1 score of 0.67 (std. 0.01), a slight but strongly significant (p-value < 0.01) improvement on the performance of the preexisting baseline model trained only on multispectral data (*S2, F1 = 0.6)*. All models that accept as input multispectral data (Sentinel-2 L2A plus vegetation indices) and any combination of the EGMS ground motion features – either only the trend features (*S2_trend*), only the full timeseries (*S2_timeseries*), or both (*S2_full_egms*) – slightly but significantly outperform the baseline *S2 model*. Model architectures that rely on EGMS surface motion data only (i.e. *full_egms, timeseries* and *trend*) perform substantially and significantly less well than those architectures that incorporate both multispectral data and EGMS data (*S2_timeseries, S2_full_egms* and *S2_trend*).

Table 3: *Performance of the tested ANN model architectures. The models are sorted by decreasing average weighted F1 score (best performing models on top). The standard deviation of F1 score across the 10 models (folds) run for each architecture is also shown. The "input features" column records which of the three main types of data input as reported in Table 2 are included in each model architecture. The performance of the pre-existing machine learning model (S2) that was trained without any EGMS data serves as a baseline and is highlighted in gray.*

Model	*Input features (see Table. 2)*	*Input layer size*	*Avg. weighted F1 score (std.)*	*P-values w.r.t.*	
				S2	*S2_full_egms*
S2_full_egms	✓✓✓	325	0.67 (0.01)	< 0.01	-
S2_timeseries	✓✗✓	318	0.66 (0.02)	< 0.01	0.67
S2_trend	✓✓✗	23	0.63 (0.03)	0.04	0.01
S2	✓✗✗	16	0.6 (0.02)	-	< 0.01
full_egms	✗✓✓	309	0.59 (0.02)	0.27	< 0.01
timeseries	✗✗✓	302	0.57 (0.03)	0.01	< 0.01
trend	✗✓✗	7	0.45 (0.04)	< 0.01	< 0.01
random	✗✗✗	0	0.39 (0.00)	< 0.01	< 0.01

Use of the full timeseries of ground motion, rather than the EGMS summary statistics, is key to performance of model architectures incorporating ground motion data. The *S2_timeseries* model architecture, which uses the full EGMS timeseries, but not the EGMS summary variables, has a performance that is statistically the same (p-value = 0.67) as the *S2_full_egms* model architecture that uses both the full EGMS timeseries and the EGMS trend variables. On the other hand, the *S2_trend* model architecture that uses the EGMS trend features but not the full displacement time series produces a slightly but significantly weaker performance. Moreover, the *trend* model architecture trained only on the EGMS summary data has the worst performance of all. An explanation is that the "trend features" are coefficients that approximate the general behaviour of the related timeseries and that smooth out subtle but important patterns within it. Model architectures trained on the full displacement timeseries may on the other hand learn from such subtle patterns to increase predictive power. Intriguingly, model architectures trained with time series of ground surface motion but without multispectral data (*full_egms* and *timeseries)* perform as well or nearly as well as the baseline model architecture incorporating multispectral data only (*S2*).

The time series of ground motion at raised peatlands appear to have distinctive relationships to ecology (Figure 2). Distinctive relationships between multispectral data and ecology have also been established recently (Ferch et al., 2026). Over the 5-year EGMS observation period, the average displacement time series within each ecotope on the Irish raised bogs tends to display long-term subsidence on the order of a few cm. Ecotopes that represent areas of good bog condition (central and sub-central ecotopes) appear on average to show systematically

slower subsidence rates and higher surface oscillation than ecotopes representing poor bog condition (sub-marginal and marginal ecotopes). Moreover, data available from Ardagullion bog indicate that the oscillation is reasonably well correlated with water table fluctuation (Figure 3).

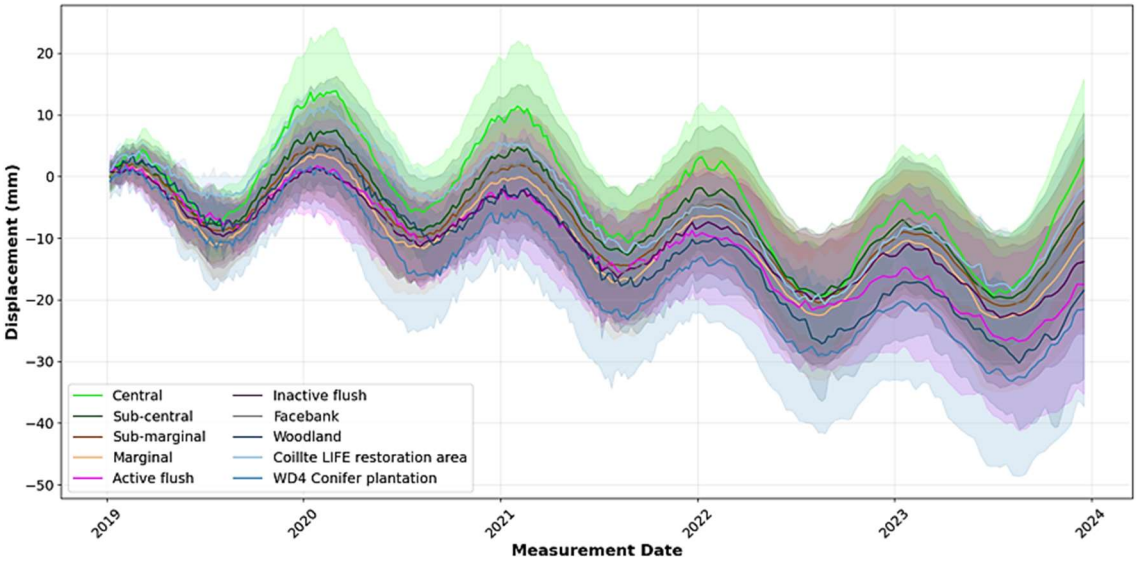

Figure 2: *Average (solid lines) and standard deviation (semi-transparent areas) of 5,246 EGMS vertical displacement timeseries on 34 Irish raised bogs as grouped by ground truth ecotope.*

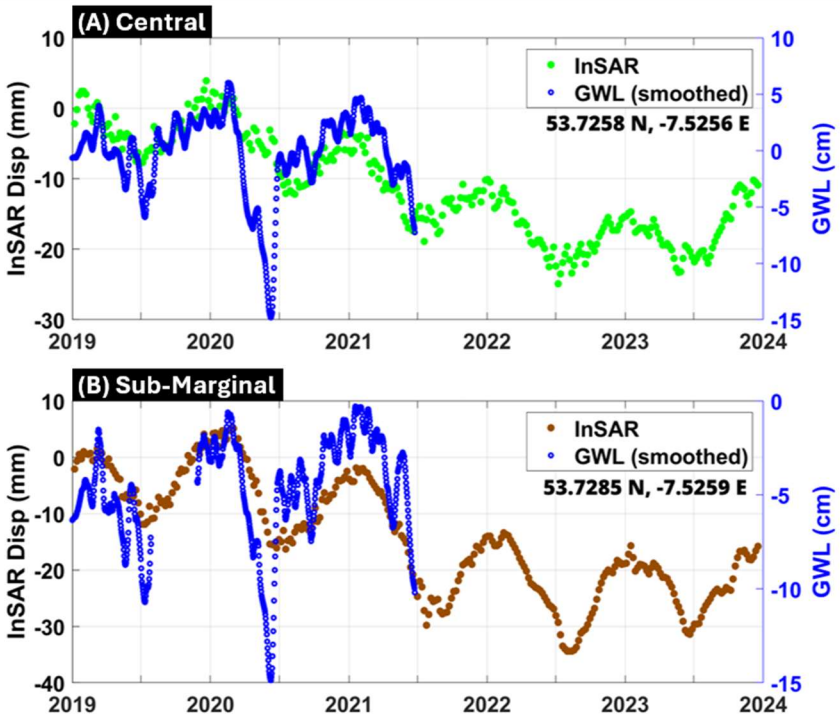

Figure 3: *Relationship of groundwater level (GWL) measured in situ to ground surface motion inferred from InSAR via the EGMS at Ardagullion bog. Note that the GWL monitoring here was limited to the period 2018-2021 and that the data are smoothed by a moving mean of 14 days. Ground motion data is original without filtering.*

It seems likely, therefore, that the distinctive variation in ground motion behavior with ecology is at least part controlled by distinctive variation in groundwater levels within each ecological community. Correlation and causality between long-term surface motions and long-term groundwater levels at Irish temperate raised bogs is nonetheless unclear (Figure 3) (see also

Hyrsiewicz et al., 2024). Further work is needed to establish empirical relationships and to constrain the controlling physical mechanisms.

A limitation for machine learning inference of peatland ecology from EGMS data is that points lie 100 m apart (Figure 1C) and so their spatial resolution is lower than the baseline inference from the 10 m per pixel Sentinel-2 multispectral data only (Figure 4). For full-bog prediction some form of interpolation (e.g. IDW interpolation (Shepard, 1968)) of model outputs is needed, but this leads to evident tiling artifacts, lack of data coverage at bog margins, and a degradation of predictive performance by approximately 24% (weighted F1 score of 0.51).

Figure 4: *Comparison of ecotope maps inferred by machine learning for Mongan bog and the ecotope map made by traditional surveying. (A) inferred map made from Sentinel-2 multispectral data only. (B) inferred map obtained by IDW-interpolation of the best performing model architecture including EGMS data (S2_full_egms).(C) ground truth ecological map from NPWS. Base image is a Sentinel-2 L2A natural colour image aquired on 11-Aug-2022.*

CONCLUSIONS AND FUTURE WORK

Use of both multispectral imagery and ground motion data together, versus using multispectral imagery alone, produces a statistically significant improvement in machine learning performance for the predictive mapping of ecological communities on temperate raised bogs. Moreover, the use of ground motion time-series alone produces a model performance almost as good as the use of multispectral data alone. A systematic variation in the average pattern of ground motion through time within the different peatland ecological communities is proposed to underpin the success of machine learning models incorporating such data. Such variation likely reflects distinct patterns of groundwater level variation within peatlands in both space and time.

To achieve more robust full-bog ecohydrological mapping, there is a need to extend the application of the relatively coarse EGMS point-based models by means of non-trivial computational approaches. Further improvement will most likely necessitate moving to bespoke InSAR time series processing (Fernandez et al., 2014) to improve measurement point resolution and to enhance the statistical discrimination of displacements associated with ecotopes. Other future work should be aimed at considering a time series of multispectral imagery and the incorporation of key information e.g. such as topology and slope (Regan et al., 2020). Finally, empirical relationships between groundwater level and surface motion at temperate peatlands must be better constrained and modelled to understand their physical connection. In any case, future extension of machine learning from local scale inferences of peatland ecology to national scale mapping is foreseen.

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No vibe coding was used to conduct this research. No Generative AI was used to write this manuscript.

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DEVELOPING A STANDARD FOR ECOSYSTEM CERTIFICATES TO REWARD FUNDING FOR IRISH PEATLANDS

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ABSTRACT

Peatland restoration and farming peat soils at a raised water table have been identified within National, and EU policy as important to reducing biodiversity loss and greenhouse gas emissions. This paper outlines the rationale and methodologies used in developing The Peatland Standard of Ireland as a quantification and certification process for the habitat and ecosystem services changes achieved from voluntary projects of peatland restoration or farming at raised water table. After public consultation the pilot version was released by Peatland Finance Ireland in 2025. The purpose is to facilitate the use of private finance to complement public funding with the aim of accelerating the pace of peatland restoration in Ireland. The Standard aims to certify reasonable evidence of change based on existing peer reviewed science models and following international voluntary market protocols. This can allow corporate reporting of mitigation projects in return for private finance to make a project viable from contribution to capital, through to modest landowner support.

Key words: *Peatland restoration, Ireland, ecosystem services, private finance*

INTRODUCTION

Ireland has a high a proportion of organic soils with approximately 1.46Mha equivalent to 20% of the land area in >30cm deep peatland (Tanneburger et al., 2017) or 23% of land area including shallow peat soils to >10cm peat (Gilet et al., 2025). Only 15-16% of this area is estimated as in a natural state or low level of degradation (Douglas et al., 2008) (Gilet et al 2025) with the country currently subject to several infringements of EU law in the management of its peatlands. (NPWS National Peatlands Strategy). Amendment to 84-85% of peatland habitats has been primarily made through drainage, extraction, domestic cut-over, afforestation, nutrient application, and to a lesser extent by over/under grazing and fire management.

Irish peatland represents a carbon store of an estimated 1-1.5 billion tonnes of carbon (C) (Renou-Wilson et al 2011) but due to the current state of degradation represents a significant land emissions source ranging from~7Mt CO_2 eq/yr (±0.4-3.4Mt C/yr) based on >30cm deep peatland >34.5% OM using Tier 1 & Tier 2 emissions factors (Aitova et al., 2023) to 12.3-13.9Mt CO_2 eq/yr based on >10cm peat depth and peaty soils >8.6%OM using tier 1 & 2 and a wider emission factor data set (Gilet et al., 2025).

In addition to climate regulation, peatland degradation impacts important ecosystem services of water regulation, water quality, human health, recreation and provision of habitats for nationally and internationally important wildlife (Bonn et al, 2014). Peatland restoration has been shown to limit the spread of wildfire (Anderson et al 2021), and carbon losses are approximately six times higher where fire events occur in drained temperate peatland sites compared to rewetted sites (IPCC Wetlands 2013).

This paper explores the rationale and methodologies for developing a quantification and certification system for habitat and ecosystem services improvements from peatland restoration.

PEATLAND FUNDING RESTORATION BACKGROUND

Public funding has been used for peatland restoration projects mostly in designated areas. Agri-environment schemes through results-based payment schemes (RBPS) have rewarded farmers in targeted zones for improved environmental field conditions. Schemes guarantee participation for only a 5-year period and are subject to a financial cap (€8k ACRES CP). Capital funding for planning projects and conducting groundworks is dependent on accessibility to EU and NPWS funding programmes.

For most landowners there has been no financial incentive to undertake peatland restoration whether to either assist in maintenance of the restoration infrastructure and more fragile post restoration habitat or to provide some compensation for the opportunity cost.

CORPORATE SUSTAINABILITY REPORTING

In July 2023 the EU adopted mandatory standards called ESRS (European Sustainability Reporting Standards) to bring quality and comparability to sustainability reporting for companies. These standards are used to fulfil the CSRD (Corporate Sustainability Reporting Directive of the EU). The 12 ESRS Standards are used to publicly report on a company's impact, and exposure to physical and financial risks and its adaption, opportunities and mitigation projects in hard metrics.

Of particular relevance, to peatland restoration projects ESRS 1, 3 and 4 cover Climate Change, Water resources, Affected Communities, Biodiversity and Ecosystems.

In April 2024, the EU approved the Carbon Removal Certification Framework (CRCF), for voluntary certification carbon removals and permanent storage in industry and farming. The methodology covering reduced emissions from peatland restoration and farming at a higher water table is currently at consultation stage with the CRCF expected to be in action by 2027. The CRCF will act as a meta-registry for national carbon schemes. The methodology for peatland rewetting importantly recognises the importance of ecosystem co-benefits, places a minimum biodiversity co-benefit requirement on projects and encourages co-benefit reporting.

PEATLAND FINANCE IRELAND

Peatland Finance Ireland (PFI), a not-for-profit company was created in 2022 by Shane Mc Guinness of University College Dublin (UCD) and Paul Chatterton of the Landscape Finance Lab with the aim of accelerating peatland restoration in Ireland. This followed a review by McGuinness and Bullock, 2020 to assess the financial needs of biodiversity conservation and restoration in Ireland. The review identified a total annual spend of approximately €29 million on excellent state backed projects but an estimated need for restoration exceeding €1.5 billion.

PFI developed the Peatland Standard of Ireland to provide a quantification and certification process to attract private finance using the voluntary market.

The use of these certificates for corporate sustainability reporting creates opportunity for private finance to provide elements of project capital, monitoring, reporting and verification costs and landowner payments where public monies are insufficient to change the status quo.

As per the international voluntary market the Peatland Standard uses legal and financial additionality tests to assess whether private finance can be used in a project alongside public money.

THE PEATLAND STANDARD OF IRELAND

In developing the Peatland Standard process, a range of state, semi-state and community stakeholder preferences were addressed including: (i) certificates (of results) rather than credits (of anticipated performance) (ii) the need for a high value certificate due to the low to moderate size of Irish land holdings and the high costs associated with restoration projects in Ireland. (iii) the wider benefits of peatland restoration rather than solely focusing on carbon (iv) the desire to work at a catchment scale for impact (v) the need to accommodate group

projects to reduce certification costs. (vi) the inclusion of semi-natural, cut over, extracted, grassland and afforested site types.

In response, the Standard aims to certify ecosystem improvements under five broad categories of Carbon, Water, Biodiversity, Community and Wildfire Reduction to recognise multiple landscape restoration benefits (Figure 1). This reflects the unique mixed, scale, ownership, range, usage and aims for peatlands and their communities in Ireland.

As many of the habitat and ecosystem improvements are generated by the same restoration activities on an area they would be sold as an indivisible bundle to one user.

As habitats, locations and project resources vary greatly, some projects will only certify one or some of the potential ecosystem improvements. Total project metrics would be used in reporting; however, landowner payments would be based on their % share of the project.

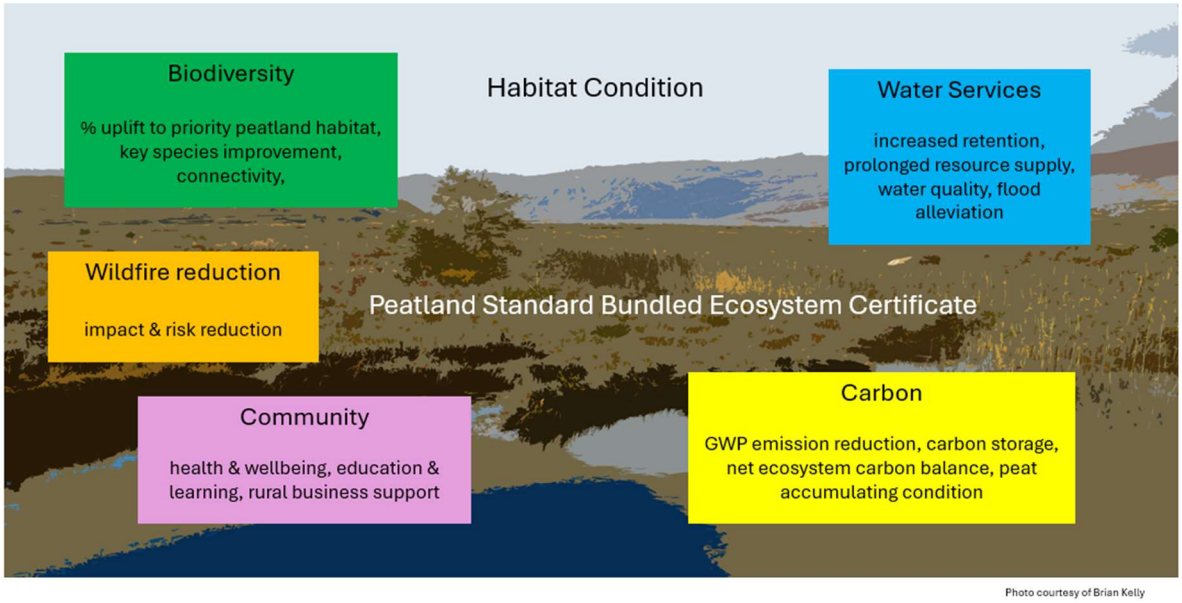

Figure 1: *The range of habitat and ecosystem services which the Peatland Standard aims to include within an ecosystem certificate. Pilot projects will primarily report on water and carbon.*

ENVIRONMENTAL PRINCIPLES, COMPLIANCE AND TRANSPARENCY

The Standard follows international environmental and voluntary market principles to ensure compliance with global standards, accounting and reporting.

Project validation and verification of ecosystem improvements will be undertaken by an independent third party working to ISO standards.

A conservative approach to quantification is adopted and assumes that the baseline condition of the peatland would not have deteriorated further if the project had not occurred.

The Standard uses results-based methodologies, to assess the impact from baseline to restoration including reference sites.

Project details including investors, landowners, project developers, reports and data outputs are to be held on an independent third-party registry linked to the CRCF registry.

The process summary is described by Figure 2.

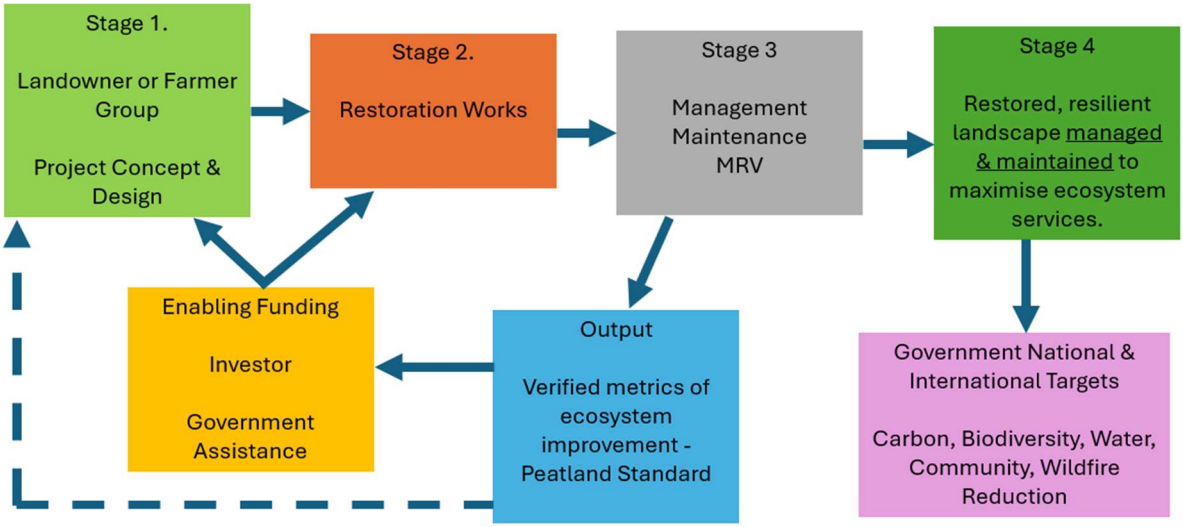

Figure 2: *Peatland Standard model for a restoration project.*

QUANTIFICATION METHODOLOGIES

Peer reviewed science models are used to evidence change between pre and post restoration years. Deductions are made for reporting to cover uncertainty to ensure conservativeness and cover risk. Investor focus is currently on water quantification and reduced GHG emissions however interest is expressed in biodiversity, flood alleviation, wildfire impact and risk reduction and water quality.

CARBON METHODOLOGY (i) Water Level

Peatland emissions are primarily influenced by water level, vegetation, nutrient status, and climate with the overriding factor being water level (Evans et al., 2021). On a national scale, tier 2 emission factors are relatively accurate for an average of tens of thousands of hectares but are currently limited in Ireland to classification as Near Natural, Grassland, Domestic or Industrial Extraction, Forestry and rewetted versions of the same. At project scale the factors can disguise wide ranges e.g. a semi-natural grass/heather bog with an annual water table depth (WTD) of 30cm will emit twice as much CO_2 equivalent greenhouse gas as a grass/heather bog at 20cm annual WTD. A peat grassland field with an annual WTD of 80cm will emit 19.41t CO_2 eq/ha/yr more than a peat grassland field farmed at an annual WTD of 40cm. (Peatland Standard Emissions Reduction Tool)

For this reason, a tier 3 methodology is used in the Standard at field scale to assess greenhouse gas emission reductions achieved from restoration. To provide a link with the National Inventory tier 1 & 2 emission factors, and to guide landowners and developers on potential project emission reductions, indicative emission factors have been collated from research data and models. Actual project emission reductions are then modelled using the site-specific tier 3 methodologies.

The annual average water table methodology as per Evans et al. (2021 & 2023) provides a model to assess CO_2 and CH_4 emission changes taking account of water level and vegetation factors. A relationship for bare peat and particulate organic carbon (POC) losses provides additional evidence (Evans et al., 2014). A future model for DOC losses may be possible but currently, research and tier 1 data are applied to assess changes in DOC, and N_2O losses after restoration.

Table 1 shows an example 1ha hydrological unit from the Peatland Standard Emissions Reduction calculator. The user selects the vegetation category from a drop-down menu and enters the unit reference, area, baseline and post restoration project year WTD (and ditch and

bare peat fractions if different from the default.) Formulas, model references and the full calculation table are available on separate tabs.

Table 1: *Hydrological unit model example for 10 ha modified Blanket Bog.*

Hydrological Unit Ref	HU2	Owner Ref	5cm BB				
Year	Indicative Vegetation Category, Pre & Post Project	Hydrological Unit Area % or (ha's)	Water Table Depth WTDe (cms)	GWP Combined Emissions t CO_2eq/ha	GWP Project Net Reduction (+ve is good) t CO_2eq	% Ditch Fraction	% Total Bare Peat including bare ditch
Baseline	Modified BB	10	20	5.77	57.70	2.5	2
Project Year	Near natural BB	10	15	2.89	28.94	0.5	1
					28.75		

Whilst the water table will vary across any site according to below surface conditions, slope and vegetation, a site is split into sub-catchments or hydrological units with monitoring points for evidence of change representing several units of similar condition (vegetation and drain spacing). Monitoring is predominantly by automatic sensors in piezometers with developments in cloud connected devices via LoRaWAN potentially allowing future cost efficiency (Table 2).

Table 2*: Project summary for illustration of a range of 1ha hydrological units from 5cm annual WT change in Blanket Bog to a 40cm annual WT change in Peat Grassland post intervention. Note model GHG emission reduction versus reportable after uncertainity and risk buffer deductions.*

	Water Level Summary (Hydrological Units)				
Assessment Unit Ref	**Sub Project Owner Reference**	**Baseline Vegetation Description**	**Project Vegetation Description**	**Project GWP C Loss Reduction t CO_2eq**	**Claimable Project GWP C Loss Reduction t CO_2eq**
HU1	5cm BB	Modified BB	Rewet Organic Soils Ti	1.51	1.09
HU2	5cm BB	Modified BB	Near natural BB	28.75	20.70
HU3	10cm BB	Modified BB	Near natural BB	5.01	3.61
HU4	10cm Grass	Grassland nutr poor	Grassland nutr poor	4.75	3.42
HU5	20cm Grass	Grassland nutr rich d	Grassland nutr rich dee	9.61	6.92
HU6	30cm Grass	Grassland nutr rich d	Grassland nutr rich dee	14.50	10.44
HU7	40cm Grass	Grassland nutr rich d	Grassland nutr rich dee	19.41	13.98

CARBON METHODOLOGY (ii) Vegetation type emission factor

Emission factors based on vegetation condition are used for specific situations such as bare peat or linear features such as haggs, gullies or face-banks. Research from semi-natural raised bogs at Clara and Abbeyleix, has split up vegetation types enabling a range of emission factors to be created for ecotopes identified as Central, Sub-Central, Sub-Marginal and Marginal (Regan et al., 2014).

Ecological assessment used to identify the change in vegetation type from the baseline to post restoration (at year 5) determines the emission reduction with the greatest reduction achieved in transitioning from Marginal to Sub-Marginal.

Bare peat features such as haggs, gullies and face-banks suffer higher losses due to their vertical nature and higher erosion pressures. An emission factor of 16.53 tCO_2 eq/ha/yr has been derived from the Aitova et al. (2023) Irish review, Evans et al. (2014) POC model and Tier 1 DOC data. Linear features are mapped as a line and a width noted to include 2m either side of the bare peat limit (Table 3).

Table 3: *Example 40ha vegetation unit model for a semi-natural raised bog using emission factors derived from Clara and Abbeyleix gas chamber ecotope research.*

Owner Reference	NECB and CO2e GWP Ecotope Balances					Baseline	Restored	Emission	%
SN raised bog	NECB	GWP AR6	Ecotope	Project Area		GWP AR6	GWP AR6	Reduction	Reduction
Vegetation Unit	t C/ha/yr	t CO_{2e}/ha/yr	(Vegetation type)	Baseline (h	Restored (	t CO_{2e}/ha/yr	t CO_{2e}/ha/yr	t CO_{2e}/ha/yr	
	-0.27	1.64	Central	0	0				
	-0.31	2.31	Sub-central	1	4	2.31	9.24		
	0.23	3.16	Sub-marginal	5	22	15.80	69.52		
	1.83	7.47	Marginal	32	12	239.04	89.64		
	4.24	15.11	Bare peat	2	0	30.22			
	4.47	16.53	Linear Hagg, Gull	0	0				
	0.11	3.51	Vege/Re-profiled	0	2		7.02		
VU1			**TOTALS**	**40**	**40**	**287.37**	**175.42**	**111.95**	**38.96**

WATER RESOURCE

Restoring peatland to maintain a high-water level through the entire year maintains a steady low nutrient content of water supply from the bog, resulting in higher stream ecosystem productivity and gives higher resilience to fluctuating climatic conditions and a less flashy release to streams and reservoirs. Whilst peat is highly porous, due to its structure and nature, only a fraction conducts water flow (Price et al 2023). Temporary water storage will mostly occur in macropores >0.25mm, (78% - Holden 2009) with micropores retaining and moving water via capillary action to vegetation even in drier conditions. The specific yield (Sy) is used to calculate the temporary increased water storage mostly in macropores and typically varies from <0.1-0.5 depending on peat damage and site type.

Due to high variability between sites and with depth, individual sites will calculate water yield (Sy) using the Water Table Fluctuation method (Bourgault et al 2017, Schutt et al 2022). To reduce project monitoring and reporting requirements ongoing development work is creating a Sy tool for site data entry, identifying when meteorological precipitation record or historical prediction could be used as a replacement for site records and a range of site type conservative default Sy reference figures for smaller sites.

Table 4: *Example calculator for increased water retention as a product of the change in annual water table from baseline year to post restoration year by specific yield. (Specific yield as given by the mean of precipitation / increase in water level for qualifying rain events).*

INCREASED WATER RETENTION VOLUME

Instructions: For each hydraulic unit or sub-project reference enter the area and mean annual baseline and restoration year water level.

Sub-project reference	Restored Project Area	Baseline Annual mean WTD(m)	Restored Annual mean WTD (m)	Water Yield (Sy)	Increased Retention Volume (m3)
Overall	100	0.25	0.2	0.2	**10000**
1	15	0.35	0.2	0.1	2250
2	30	0.27	0.22	0.3	4500
3	25	0.25	0.21	0.2	2000
4	30	0.2	0.18	0.3	1800
			Total		**10550**

Following the Volumetric Water Benefit Accounting (VWB) protocol (World Resources Institute 2025) the increased water retention volume from peatland restoration is used as reporting for VWB (Table 4).

BIODIVERSITY

Most international biodiversity methodologies (over 53 by 2024) take a holistic approach e.g. the Wallacea methodology uses a basket of 5 metrics including both structural and non-structural groups. As damaged peatlands have different biodiversity, not necessarily less a biodiversity uplift can be calculated from a mean of progress towards priority habitat in good condition via a community similarity in qualitative and quantitative metrics. Certificates of

biodiversity uplift are based on a hectare of 1% uplift and are nuanced by incorporating conservation value, uncertainty and a median across metrics.

Added weight is given for a dominant metric which has a major impact higher up the food-chain e.g. sphagnum, ecosystem structure, invertebrates. Higher species highly dependent on factors outside of a site's habitat provision may be avoided particularly for a small site e.g. breeding waders, due to meso-predator impact. The selection of 5 metrics can be flexible for individual projects as localities or communities may have cost, research preferences.

For pilot sites, data will be collected directly. For later catchment projects of multiple landowners within agri-environment schemes potentially data would be collected both directly on reference sub sites and as proxies on all sites via field scorecards.

ADDITONAL ECOSYSTEM REPORTING

The Peatland Standard Ecosystem calculator includes additional metrics (some under development) which may be used by projects depending on funding. For example, overland flow velocity and erosion loss is directly related to the extent and type of vegetation cover, and this impacts delivery from peatland catchments.

Modelling average flow depth against velocity, Holden et al 2008 showed a consistent flow rate reduction benefit of increasing sphagnum content, increasing sedge or grass cover and reducing bare peat cover due to effective roughness and vegetation structure. The reduction benefit is lower at higher flows, over 1cm flow depth due to physical vegetation effects.

The calculator includes a tool which uses Holdens data to conservatively assess the % reduction in surface flow rate due to restoration changes in vegetation.

A response function for Particulate organic Carbon (POC) loss from bare peat derived by Evans et al 2014 enables a tool to use the change in bare peat cover from restoration as a proxy for reduced POC erosion loss.

FUTURE VERSIONS

Methodologies for assessing change will change with published research, particularly on the use of satellite data for water table assessment, ecotope identification, tier 2 emission factors, surface elevation trend and pattern, association of agri-environment scorecards to site change metrics and biodiversity automatic monitoring.

ACKNOWLEDGEMENTS

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DIGITAL TOOLS FOR PEATLAND RESTORATION PROJECTS
APPLICATION WITHIN THE TÓCHAR WETLANDS FEN RESTORATION PROGRAMME

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ABSTRACT

Peatland restoration projects are increasingly being delivered at large spatial scales and under ambitious timeframes, creating challenges for data integration, field coordination, and stakeholder engagement. Digital tools are therefore becoming critical components of restoration programmes. This paper presents the digital workflows developed by Arup in support of the fen restoration programme delivered by the Tóchar Wetlands Restoration Project across Ireland. The project involves the development of restoration plans for thirty-six fen sites within a two-year timeframe and requires the integration of hydrological, hydrogeological, ecological, and land management data.

A suite of digital tools based primarily on geographic information systems (GIS), field data capture platforms, remote sensing datasets, and stakeholder management databases were implemented to support project delivery. A centralised web-based mapping portal was developed to integrate over 250 spatial data layers including ecological survey data, water monitoring data, environmental regulatory datasets, and geological mapping. Field data collection was standardised using mobile GIS applications allowing real-time synchronisation of hydrological, ecological and peat depth observations. Remote sensing products, including Copernicus wetness indices, vegetation productivity metrics and InSAR ground deformation data, were used to prioritise field investigations and assess peatland condition. High-resolution lidar surveys were used to analyse drainage networks and support restoration design.

The paper demonstrates how digital tools can significantly improve efficiency, transparency and collaboration in large-scale peatland restoration programmes, and highlights opportunities for integrating monitoring and implementation tracking in future phases.

***Key words**: peatland restoration, GIS, remote sensing, fen hydrology, digital workflows.*

INTRODUCTION

Peatlands are among the most important ecosystems in Ireland, providing biodiversity habitat, carbon storage, water regulation, and cultural value, but many have been degraded by drainage, peat extraction, agriculture, and forestry. Restoration has become a key national and European objective in response to climate, biodiversity, and water management policies. Fens, which are groundwater-dependent, are particularly sensitive, making hydrogeological understanding central to their restoration through characterisation of flow systems, drainage impacts, groundwater–surface water interactions, and hydrological restoration measures.

The Tóchar Wetlands Restoration Project (https://www.tocharwetlands.ie/), Ireland's largest coordinated fen restoration initiatives, aims to develop restoration plans for thirty-six fen sites across diverse hydrogeological, land use and ecological settings (Figure-13). The programme's scale and two-year timeframe required efficient workflows to integrate large volumes of environmental data, coordinate multidisciplinary teams, and support field investigations. This paper presents the digital approaches developed by Arup, combining web-based GIS platforms, mobile data collection, remote sensing datasets, and stakeholder databases to support site assessment, monitoring, and restoration design.

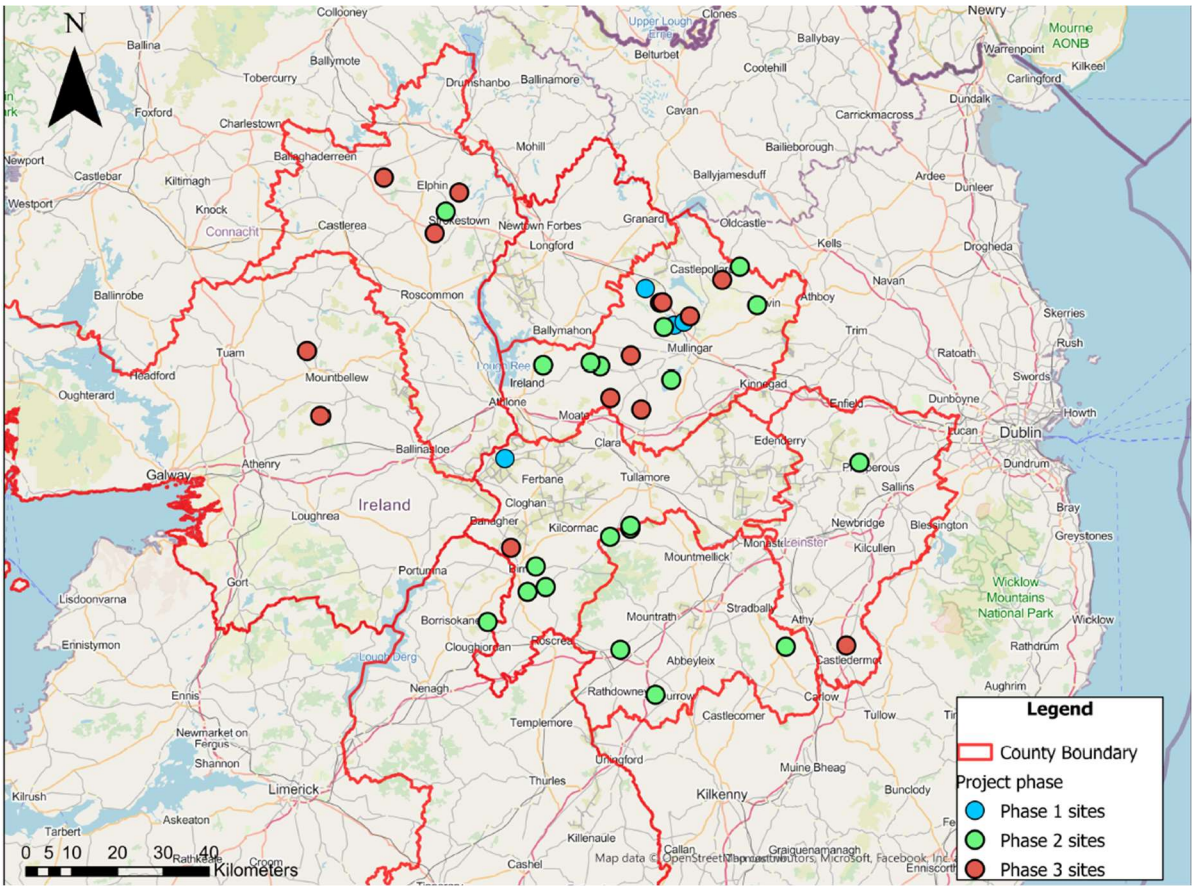

Figure-13: *Spatial Overview of the Tóchar Wetlands Fen Restoration Sites.*

PROJECT CONTEXT: FEN RESTORATION PROGRAMME

Fens are groundwater-dependent peatlands whose ecological condition is sensitive to hydrological change. Restoration measures typically aim to re-establish natural hydrological conditions, including blocking or infilling drainage channels, re-establishing natural water levels, reconnecting groundwater discharge zones, and managing vegetation and invasive species.

The Tóchar Wetlands project programme is linked to EU Just Transition Funding. Developing restoration plans for thirty-six geographically dispersed sites within two years posed significant logistical and analytical challenges, addressed by a multidisciplinary team of ecologists, hydrologists, hydrogeologists, geospatial specialists, and civil engineers working within a shared and accessible data environment.

DIGITAL METHODOLOGY

GIS WEB MAPPING PLATFORM

A principal component of the project was the development of a web-based GIS platform using ArcGIS technology, referred to as the Atlas portal within Arup, integrating over 250 spatial datasets relevant to peatland restoration (

Table-4). Figure-14 shows the portal interface, including site boundaries and key local and regional layers.

Table-4: *Spatial Data Categories Integrated into the Atlas GIS Portal.*

Category	Data Included
Project Data	Project site boundaries, historical survey information from the NFS, habitat and drainage mapping, ecological monitoring points, water monitoring locations and field notes.
Biodiversity and Habitat Data	Species location data (National Biodiversity Data Centre) and habitat datasets (National Parks and Wildlife Service, including Article 17 reporting datasets for protected habitats and species), SAC, SPA, NHA and pNHA.
Environmental and Water Data	Water Framework Directive rivers, lakes, and canals; WFD ecological status classifications; water abstraction register; section 4 discharge licences; Targeted Agricultural Modernisation Scheme data; Pollution Impact Potential (PIP) maps for nitrogen and phosphorus.
Geological and Hydrogeological Data	Aquifer classifications; Karst datasets; groundwater wells and source protection zones; bedrock geology; groundwater recharge maps; groundwater vulnerability; quaternary sediments and soils.
Other Spatial Datasets	Archaeological sites and monuments; architectural heritage inventories; electricity infrastructure (Electricity Supply Board); national administrative boundaries; LiDAR datasets (Open Topographic Viewer)

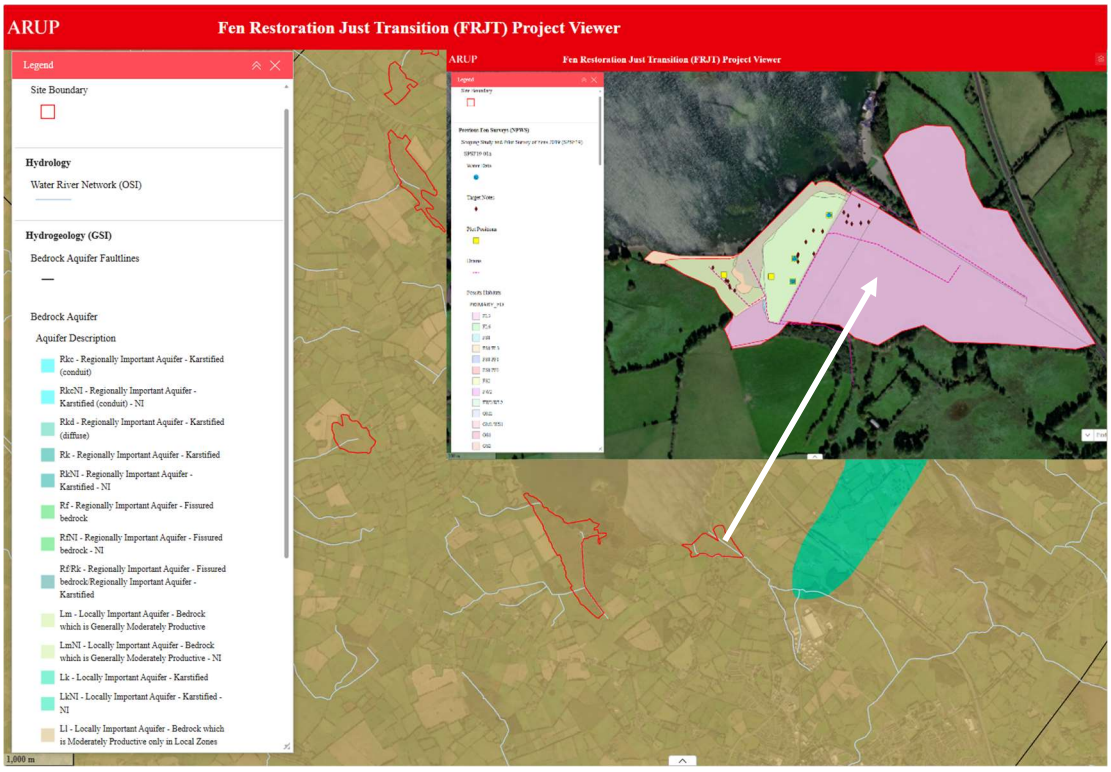

Figure-14: *Atlas Portal interface showing site boundaries and key layers, including local data and regional datasets.*

Satellite datasets from the Copernicus programme, including wetness and plant productivity indicators, were also incorporated. This single web mapping environment enabled rapid desktop assessments prior to field visits and allowed all project team members to access the same information.

GIS PHOTO VIEWER

A dedicated web mapping interface was developed to manage geolocated site photographs from field surveys, with each point opening the image along with metadata such as date, location, and photographer. This tool allows rapid visual review of site conditions, tracking of changes over time, improved team coordination, and reduced duplication of site visits. The

photographic record has proven particularly valuable during interdisciplinary discussions and design workshops. These features are illustrated in ***Figure-15***, which shows the GIS Photo Viewer interface.

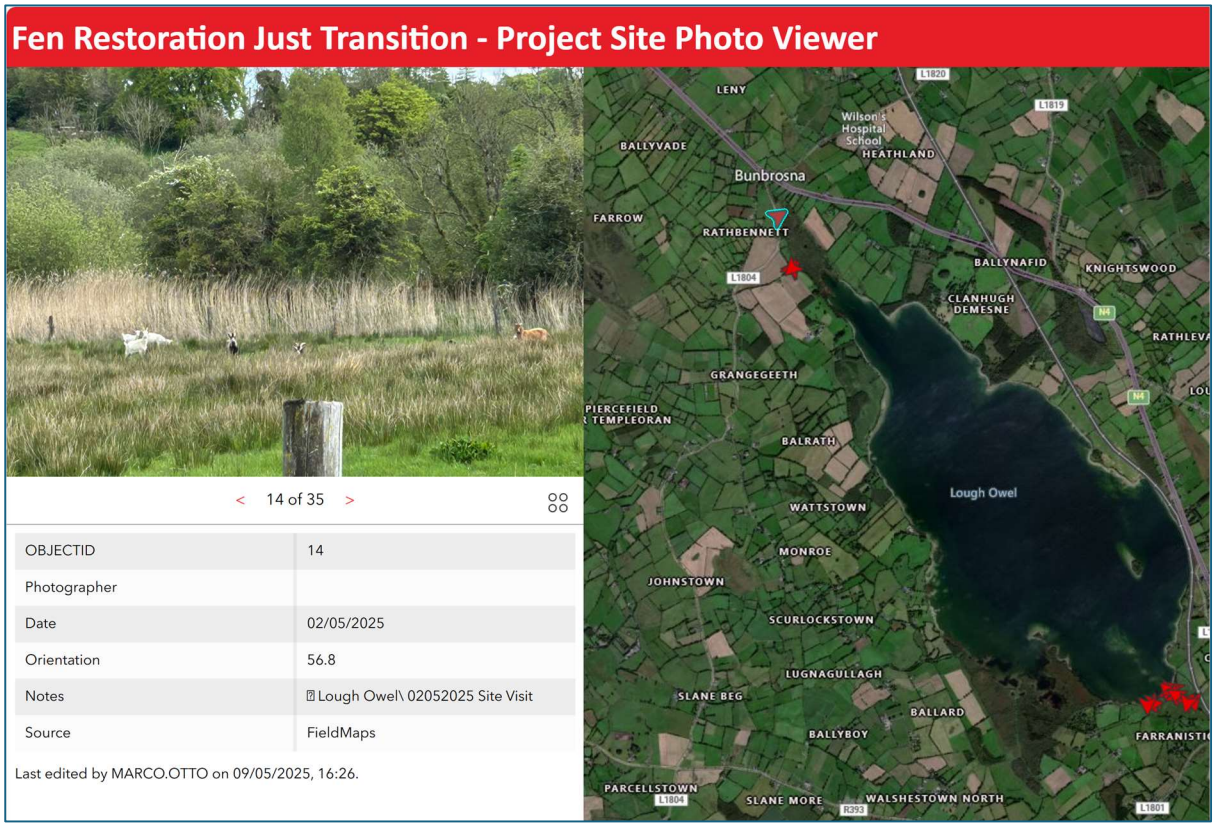

***Figure-15**: GIS Photo viewer interface.*

MOBILE FIELD DATA COLLECTION

Field data collection was standardised using mobile GIS applications (ArcGIS Field Maps), allowing photographs and notes to be attached to each observation and synchronised with the central GIS portal for immediate access. A structured data architecture ensured consistent recording of environmental observations across all sites, including additional hydrological data such as channel dimensions and flow conditions. Survey categories and data collected are summarised in the Table 5 below, while the Figure 16 shows examples of the field data collection interface.

Separate data entry forms were developed for different water feature types including Spring/Flush, Lake, River/Stream and standpipe.

***Table 5:** Summary of field survey categories and the associated data collected at project sites.*

Survey Categories	**Data Collected**
Soil Monitoring	Peat thickness and spatial distribution
Water Monitoring	pH, Electrical Conductivity (EC), Dissolved Oxygen (DO), Nitrate and Phosphorus
Ecological Monitoring	Vegetation surveys and habitat condition
Pressures & Threats	Waste dumping, Invasive species, eutrophication indicators

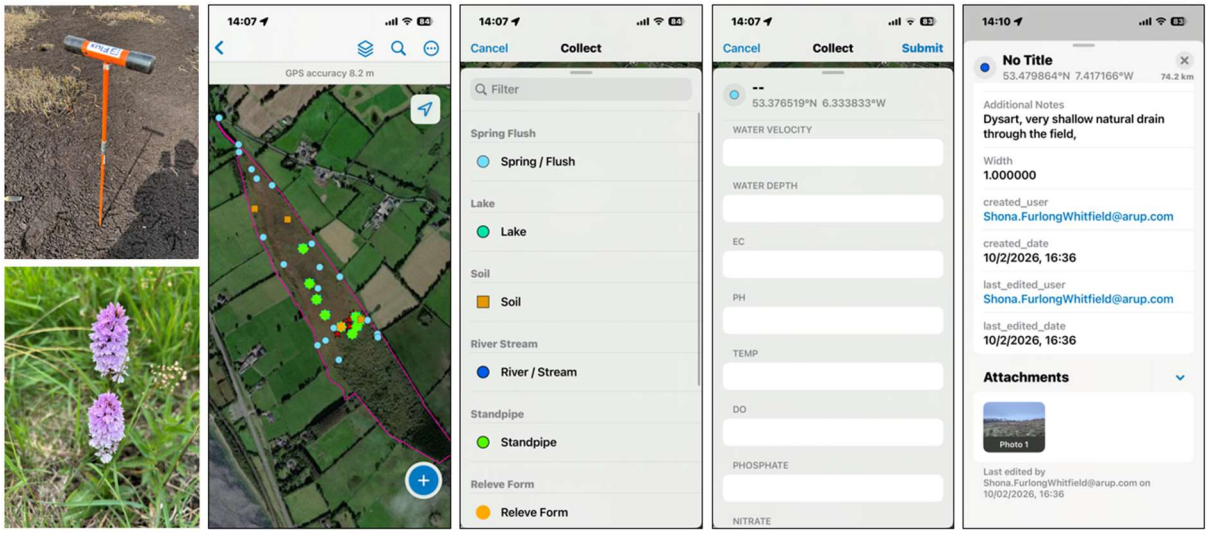

Figure 16: *Field Data Collection interface.*

REMOTE SENSING APPLICATIONS

Remote sensing data were key for screening and prioritising field investigations across the thirty-six sites, providing an efficient basis for identifying areas requiring detailed assessment. Two Copernicus-derived datasets were particularly valuable: the Wetness Index, indicating surface moisture conditions and potential drainage impacts, and plant productivity, highlighting areas of excessive growth that may reflect nutrient enrichment or altered hydrology (Figure 17).

Integrated within the GIS platform, these datasets supported targeted field surveys and the placement of monitoring installations such as piezometers or dip wells.

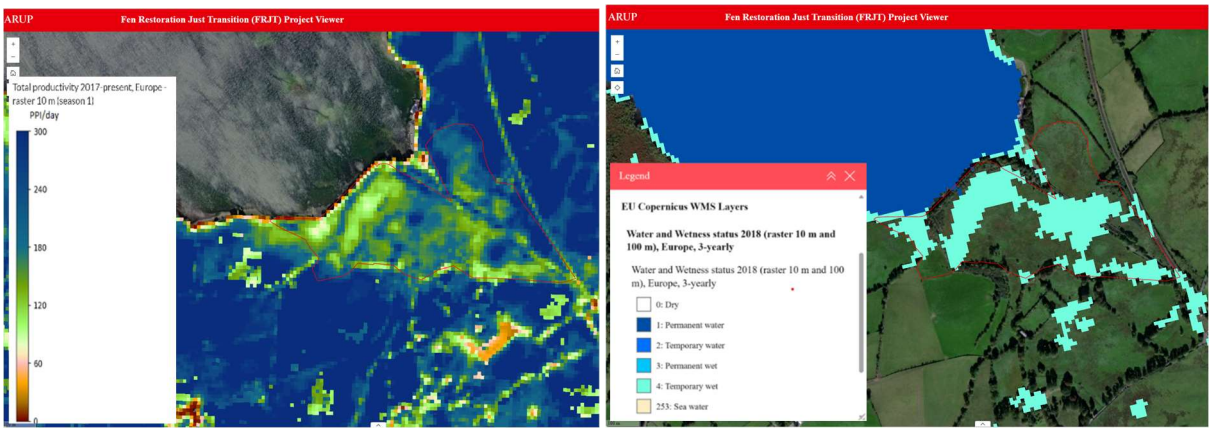

Figure 17: *Copernicus-derived datasets showing Plant Productivity (left) and Wetness Index (right).*

LIDAR AND HYDROLOGICAL ANALYSIS

High-resolution LiDAR surveys and drone-based photogrammetry were conducted across all project sites. The LiDAR datasets provide detailed digital elevation models essential for understanding site hydrology, enabling identification of historic drainage channels, mapping of peatland micro-topography, delineation of catchment areas, and detection of potential hydrological connections. Integrated into the GIS portal and analysed with ArcGIS Pro, the data support restoration design by identifying drainage networks and flow paths, informing interventions such as drain blocking, setting target water levels for peat dams, and evaluating hydraulic gradients. Figure 18 combines historical drainage mapping with LiDAR-derived topography.

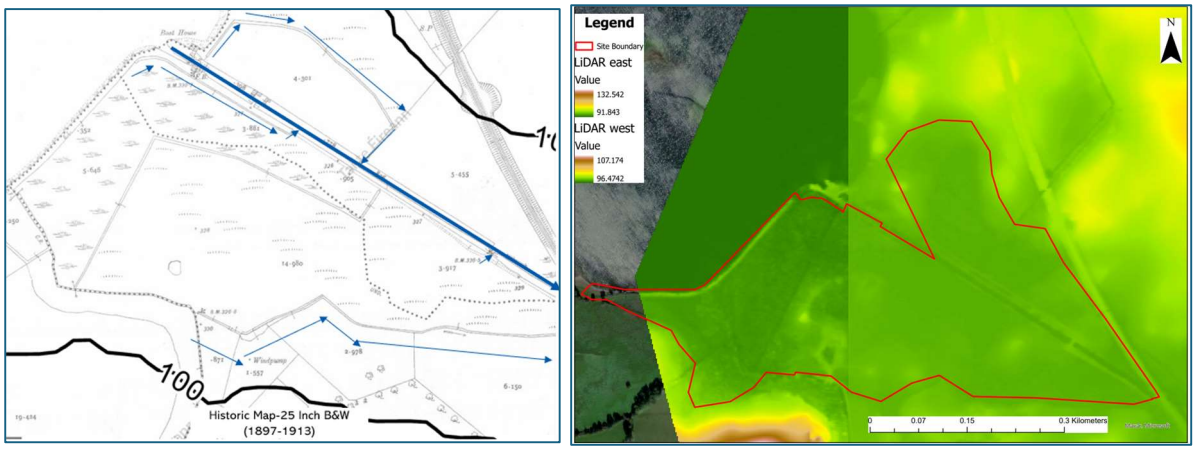

Figure 18: *Drainage network on historical map (left) and LiDAR-derived digital elevation model (right).*

LANDOWNER ENGAGEMENT MANAGEMENT SYSTEM (LEMS)

Engagement with approximately six hundred landowners is a key part of the restoration programme. Arup have developed a GDPR-compliant Landowner Engagement Management System (LEMS) for large infrastructure projects. The landowner database is integrated with the GIS portal, with each record including contact information, communication history, access permissions, and associated documentation. Land folio data was provided to Arup for the purpose of the project by the Department of Housing, Local Government and Heritage. Correspondence can be attached, and parcels are colour-coded in the GIS to show access permissions, improving field planning. LEMS also supported six public engagement events by providing quick access to land parcel maps and related information.

INSAR MONITORING OF PEATLAND DYNAMICS

The project has explored the use of satellite data from the European Ground Motion Service. Interferometric Synthetic Aperture Radar (InSAR) provides millimetre-scale measurements of ground movement, revealing seasonal peat surface fluctuations, or “mire breathing.” Analysis showed that healthy peatlands have strong seasonal fluctuations around a stable long-term equilibrium, drained peatlands show seasonal fluctuations with a gradual downward trend indicating subsidence, peatlands with reduced thickness display smaller seasonal amplitudes, and recently restored peatlands may show a reversal of subsidence as water retention improves. These patterns are illustrated in Figure 19 which highlights both the seasonal “mire breathing” and an overall downward trend indicating subsidence due to drainage.

FUTURE DEVELOPMENT: RESTORATION TRACKING DASHBOARDS

The next phase of digital development will focus on monitoring restoration implementation. Proposed measures, such as peat dams, drain blocks, and vegetation management zones, will be added to the GIS as spatial datasets. Field teams can view these measures in the mobile GIS app, confirm task completion, and attach photographs and notes. This information will feed interactive dashboards showing project progress, with metrics like percentage completion summarised by site or region, enabling near real-time tracking for managers and stakeholders.

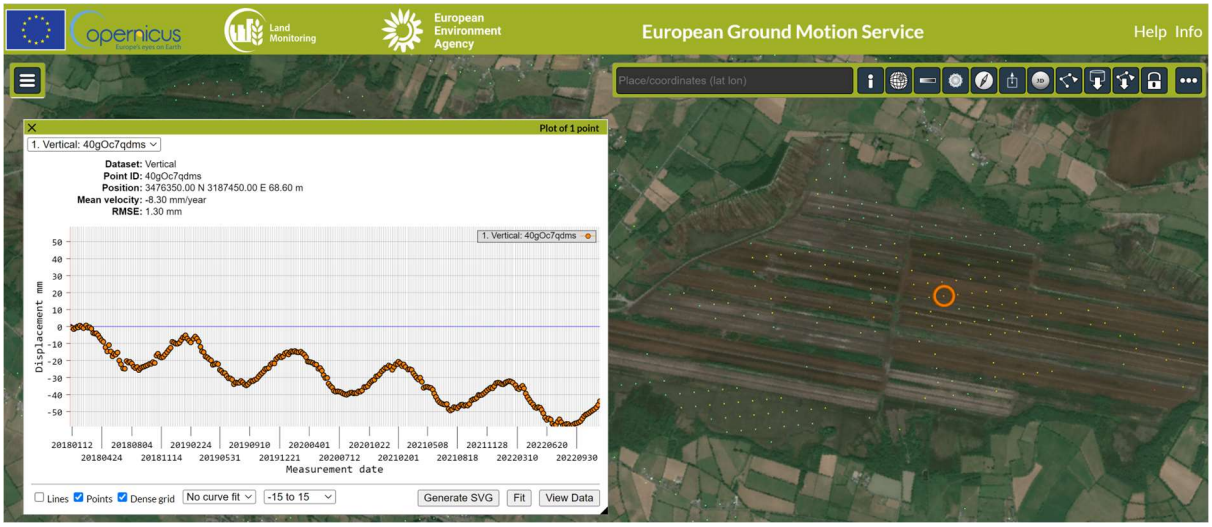

***Figure 19**: InSAR-derived seasonal peat surface fluctuations.*

CONCLUSIONS

Large-scale peatland restoration relies on integrating environmental datasets, multidisciplinary expertise, and stakeholder engagement. The Tóchar Wetlands programme demonstrates how GIS, mobile data collection, and remote sensing can enhance project delivery by improving data access, targeting field investigations, standardising monitoring, strengthening interdisciplinary collaboration, and coordinating landowner engagement. LiDAR and InSAR provide valuable insights into peatland hydrology and support restoration monitoring, highlighting the increasing importance of digital tools for evidence-based planning and long-term programme management.

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WATER-SHARE IRELAND, A GOAL GLOBAL PROGRAMME: DELIVERING WATER & SANITATION IN DEVELOPING COUNTRIES

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ABSTRACT

Water-Share Ireland is a collaborative partnership with GOAL Global in enabling improved water and sanitation in developing countries. At the core of this work is the concept of capability building, enabling communities to improve their lives through enabling better health, education and economic systems that are sustainable.

For rural communities in Uganda, solar power opens up the opportunity for piped systems using borehole pumps with basic controls and storage to make clean safe water available to households, village clinics and schools. Apart from the health benefits, this can greatly reduce the labour (by women and girls mainly) of water collection from remote handpumps. In turn, this frees up time for continued education and alternative economic activity.

In Freetown Sierra Leone, GOAL has enabled collection of latrine sludge which was initially disposed on to the town landfill on which 6,000 people live and earn a living. By developing a scheme to dewater the sludge (filtration through geobags after polymer flocculation), a viable sludge management plant has helped divert the sludge to other uses. Water-Share was key to providing the technical expertise to build, commission and support plant operations. This has opened up the opportunity for further sludge processing with the objective of carbon replacement in cooking as a sustainability objective.

In Northwest Syria, Water-Share has played a growing role in providing technical support to GOAL including leakage checks, groundwater assessments and reviews of sewerage, wastewater and water plants in an area affected by protracted conflict.
In Zimbabwe, Water-Share is working to pilot a private water enterprise that could make clean safe water available for unplanned development in the suburbs of the capital Harare, where local wells are polluted and citizens are at risk of cholera and dysentery – diseases largely eliminated where water is safe to drink.

Key words: *Groundwater development, solar pumping, faecal sludge management, sustainable development.*

BACKGROUND TO WATER-SHARE IRELAND

Water-Share Ireland (Water-Share) is a strategic partnership between the Irish water sector and GOAL Global, that enables more effective delivery of water and sanitation projects in least developed countries. This strategic collaboration provides funding, technical, professional, materials and research expertise from the Irish water sector, via Water-Share, to GOAL's water, sanitation and hygiene (WASH) programmes. Water-Share functions and operates within GOAL's existing oversight and governance framework.

WASH programmes are vital for the wellbeing of communities across the globe. Everyone requires clean, safe water for drinking, cooking and washing. Polluted water isn't just dirty – it can be deadly.

Since 2019 the Water-Share partnership has delivered numerous projects related to drinking water supply, basic sanitation, faecal sludge management, training and capability building in GOAL's countries of operation. This experience has shown that a partnership like this can add real value to the work GOAL and its partners are doing on the ground in support of vulnerable communities. Water-Share and GOAL's work is aligned with the United Nation's

Sustainable Development Goals (SDGs) and provides a framework for our sector companies to fulfil their Corporate Social Responsibility and staff engagement goals.

In delivering for communities without basic services, Water-Share affords sector companies and volunteers an opportunity for cross-sector collaboration in support of GOAL programmes, offering real tangible benefits of clean water, healthy communities, sustainable employment, education and social progress.

WATER-SHARE DELIVERING CLEAN WATER TO COMMUNITIES IN UGANDA

Groundwater Investigations in Namayingo District

Uganda's Ministry of Water and Environment (MoWE) is moving rural communities away from single hand-pump systems toward piped water schemes. this requires identifying reliable and good-quality groundwater sources, as treating surface water is not sustainable in these communities. Water-Share worked with GOAL to explore options for sustainable water supply in several rural counties in south-east Uganda. Irish hydrogeologists guided GOAL's local teams, particularly in areas where groundwater is scarce or harmful to health.

The project was divided into three phases, to be implemented sequentially as funding permitted:

- **Phase 1:** Investigating potential sources that might support larger abstractions, with demographic and topographic data gathering and analysis.
- **Phase 2:** Feasibility assessment to identify the scope for pipe-based systems from the most promising source using solar powered pumps, mini-reservoirs and pipes linking to multiple water standpoints.
- **Phase 3:** Having identified a promising source at Nsibonwe, this phase was to confirm the water available was of the right quality and volume to support regional piped water across the Buwoya area.

Phase 1 included a systematic assessment of known water resources in the Namayingo district. We collated available information on national and regional databases and validated this through community engagement in key areas. Ultimately, six sites were selected after detailed workshops involving GOAL, national and regional district teams. Detailed investigations (including camera surveys, re-drilling, pump testing and chemical analysis) identified Nsibonwe as the strongest candidate for further investigation. The locations of the six boreholes investigated are shown in Figure 1.

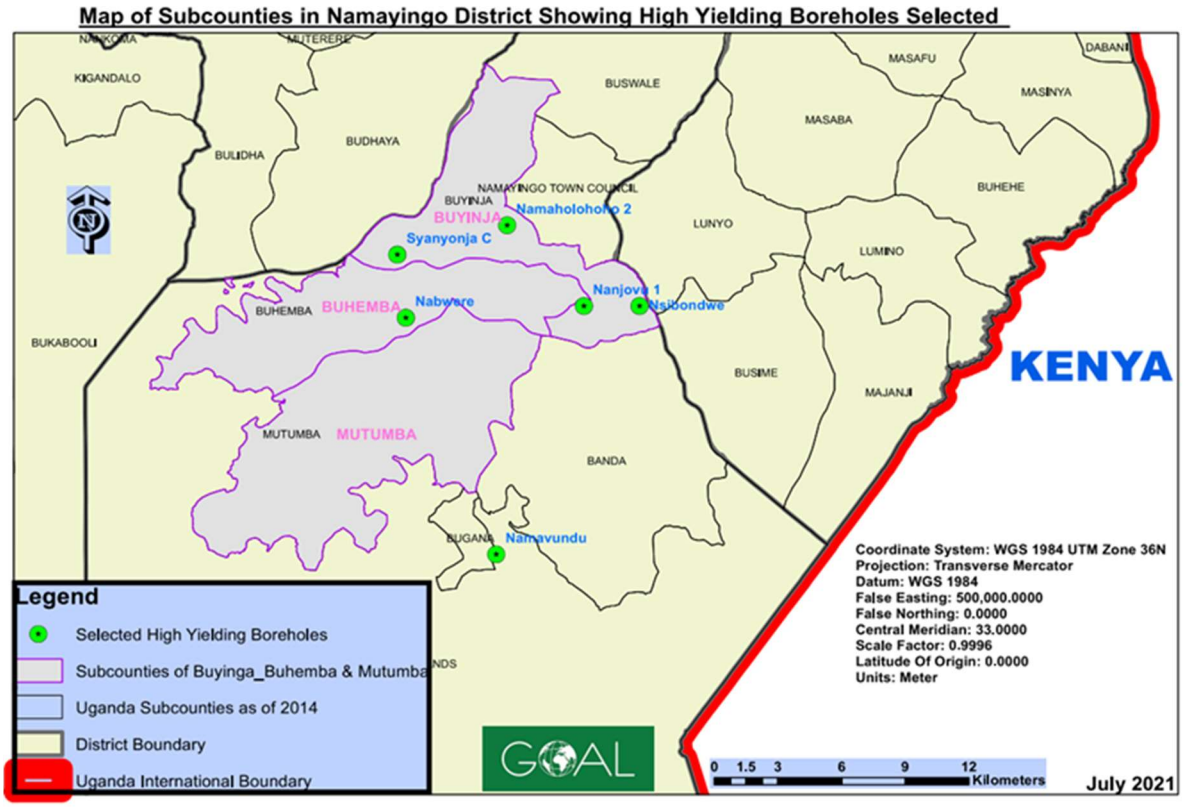

Figure 1: *Map of boreholes selected*

In order to deliver this regional water, it will be necessary to prove that the source can meet demand (minimum 10 litres per head and 2% annual growth). While this work continues, Water-Share has already delivered a number of local schemes as set out below.

Mulombi Public Water Supply – Eastern Uganda

- **Phase 1:** commissioned and handed over to the Ministry of Water to operate in early 2024, serves **3,000 people** including three schools.
- The source can support **up to 11,000 people**.
- **Phase 2:** recently commissioned; extends service to **6,000 more people**, including four schools and a health centre.
- This work was made possible through financial support from Ward & Burke Construction Ltd.

Mogadishu Public Water Supply – Northern Uganda

- Hydrogeological surveys and exploratory drilling identified a source yielding **60m³/day**.
- A piped scheme was designed and tendered in 2025 with **construction scheduled for completion in 2026**.
- Will serve **3,000 people initially, growing to 6,000 by 2045**.
- Advance-funded by a contribution from the Father O'Toole Trust and represents a critical investment in a highly vulnerable, water-insecure region in northern Uganda.

Buwoya Public Water Supply – South East Uganda

- Work continues to deliver a large-scale system for **12,000 potential people**.

- Based on our earlier studies in Namayingo District, a geophysical survey, including 2-D resistivity, has been completed in the Nsibondwe area and **potential sites for test drilling have been identified**.
- Funding of €25,000 - €35,000 is currently being sought for drilling works that could unlock larger investment to construct a regional scheme.

Ongoing Technical Support

Water-Share Ireland continues to provide critical technical expertise across these projects, with members contributing to hydrogeology (Arup, Tobin), design reviews (Ryan Hanley, Tobin, Egis), and network modelling (Ryan Hanley, Uisce Éireann).

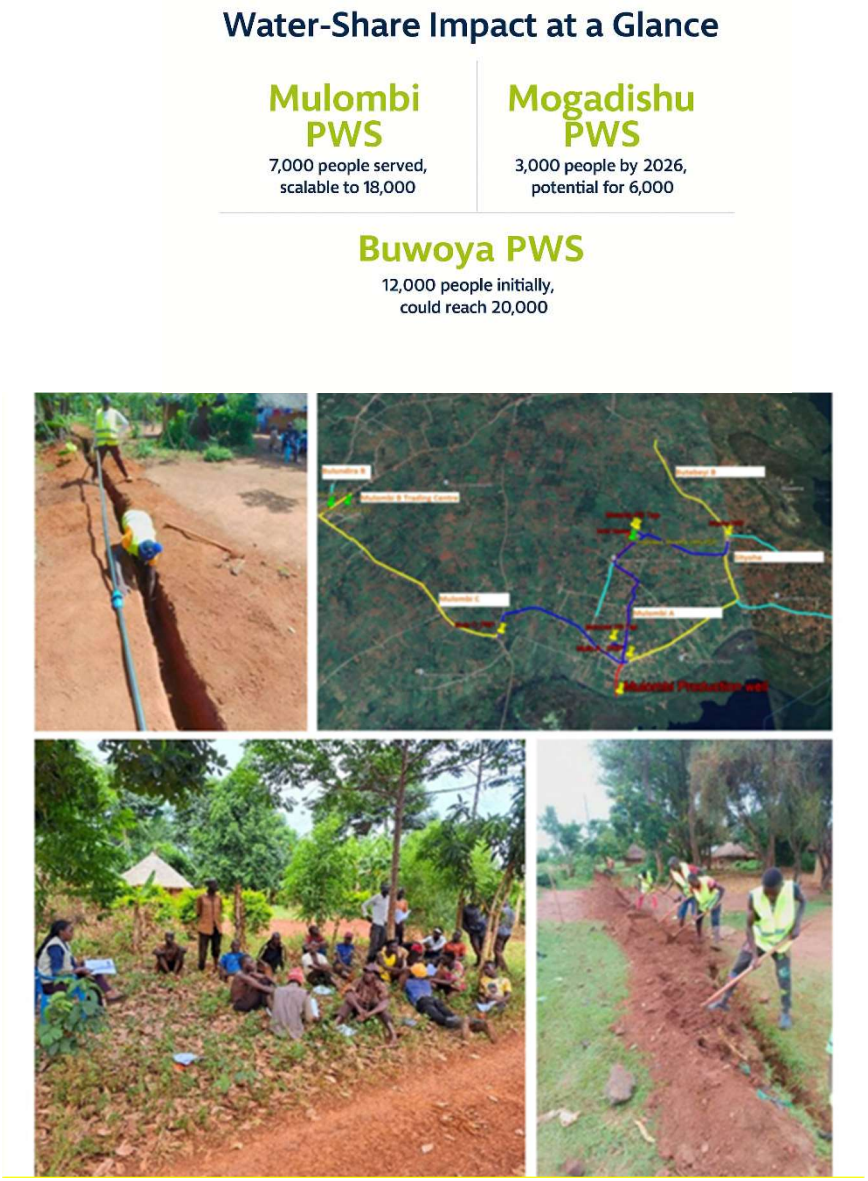

Figure 2: *Mulombi PWS Scheme Layout and Construction.*

WATER-SHARE DELIVERING & IMPROVING FREETOWN'S FIRST FAECAL SLUDGE PLANT, SIERRA LEONE

GOAL Sierra Leone, in partnership with Freetown City Council, FCDO, and Water-Share, constructed Freetown's first Faecal Sludge Treatment Plant (FSTP) at Kingtom Landfill. The plant was completed in 2021 and consists of inlet screens, a mixing chamber, polymer dosing and mixing systems, geobags, anaerobic baffled reactors, and interconnected pipework. Using geobag technology the plant treats approximately 20% of Freetown's faecal sludge.

The plant diverts up to 12 tankers of liquid sludge away from the Kingtom Landfill reducing health risks for the 6,000 people living on and around the landfill and limiting pollution to local streams. The plant has proven robust and the challenge for GOAL is to establish a revenue stream that would allow Freetown City Council to take on its operation.

A Water-Share assessment in March 2024 identified several operational challenges and recommended targeted improvements, which formed the basis of a rehabilitation project completed in 2024/2025 with major support from EPS in Ireland.

Works Completed (2024/25)

Based on Water-Share's recommendations, a range of equipment and materials were manufactured and pre-assembled in Ireland and sent to Sierra Leone. Key works included:

- **New inlet screens;** replacing corroded screens to manage rags and other debris in sludge reception pit.
- **Polymer dosing system**: Replaced corroded metal cage with a more durable structure, applied anti-rust protection, and installed a standby dosing unit in case of breakdown.
- **Electrical and civil works**: Evaluated damaged electrical connections and restored electricity. Completed civil works, including plumbing and concrete works, to enhance safety and durability.
- **Flocculation system**: Installed a new stainless-steel flocculator with two knife valves (positioned 180 degrees opposite each other) to regulate flow and generate the necessary turbulence to improve mixing of sludge with polymer, thereby enhancing efficiency.

Results and Impact

The rehabilitation works significantly improved operational efficiency, resilience, and safety. Key outcomes include:

- **Improved treatment performance**: New inlet screens and new mixing and flocculation systems have enhanced sludge dewatering, ensuring more consistent performance of the geobags. Operators observed improved effluent quality (reduced suspended solids) due to lighter effluent turbidity during dewatering.

  Higher operational efficiency: The upgraded polymer dosing system, standby unit and new flocculator significantly reduced blockages, downtime, and maintenance efforts. Extending sludge delivery pipes to the last five geobags eliminated temporary connections, simplifying operations, reducing manual handling, and ensuring more reliable sludge distribution.
- **Enhanced safety and durability**: Electrical and civil works have strengthened structural integrity and reduced hazards, creating a safer working environment.
- **Stronger stakeholder confidence**: Demonstrated our commitment to maintaining a functional, high-quality, sustainable facility

Figure 3: *Images of Freetown Faecal Sludge Plant*

Next steps for Freetown

With these works complete, the focus shifts toward transforming waste into smokeless briquettes through a system of dewatering, degassing, and drying, supporting both environmental sustainability and local economic development. This step-change aims to monetise waste, reduce reliance on traditional fuels, and create a circular economy model for sanitation and energy in Sierra Leone.

This innovative work is supported by generous donor funding from Irish Aid and FCDO, along with essential technical expertise and funding from Water-Share Ireland members, including Nicholas O'Dwyer (RSK), EPS, RPS (a Tetra Tech Company), DCU, Joe O'Driscoll, and Uisce Éireann.

STRENGTHENING WASH SYSTEMS THROUGH TARGETED TECHNICAL SUPPORT IN IDLIB PROVINCE, NORTHWEST SYRIA

Amid a challenging and volatile context, Water-Share Ireland continues to support GOAL in advancing essential technical assessments to strengthen WASH systems across Idlib province.

Recent efforts include a review of leakage levels in the water distribution network for Salqin city, an assessment of groundwater potential in the face of climate change, and technical reviews of sewage networks, the wastewater treatment facility, water distribution network, solid waste sites, and solar infrastructure.

This work is made possible through the expertise of Water-Share Ireland members, including RPS (a Tetra Tech Company), Arup, Glanua and Nicholas O'Dwyer (RSK). Their contributions

are vital to protecting and improving water access in one of the world's most complex humanitarian settings.

Since the fall of the Assad regime, GOAL has increased its footprint in Syria and has recently approached Water-Share to seek support for restoration of water services organisation structures and institutional development, network management (especially leakage), restoration and operational support for wastewater and water plants. Much of the infrastructure has been badly degraded by bombing and will need large scale investment. The immediate challenge is to determine to what extent Water-Share members can offer support in tackling priority issues. Syria continues to face a severe water deficit due to prolonged drought, with growing pressure on water resources for both household use and irrigation.

A NEW MODEL FOR SAFE DRINKING WATER IN ZIMBABWE

In Harare's densely populated informal suburbs, limited public water access has left communities reliant on community-managed borehole systems, which are not sustainable. With funding generously provided by John and Mary Cradock, Water-Share Ireland and GOAL are exploring a new approach: piloting private sector-operated water kiosks to provide safe, affordable, and sustainable water.

Following engagement with local authorities, a pilot project is being proposed in Hopely Farm suburb, where residents currently rely on shallow, unsafe wells. The proposed solution includes a secure kiosk with a solar-powered borehole, chlorination, storage, and automated dispensing with a digital pre-payment system. In addition, a critical component of the kiosk will be to demonstrate to the local authorities how remote sensing can facilitate service provider performance monitoring and promote quality services to local residents. A Business Case has been completed with a local provider, and this project is moving to implementation.

Figure 4: *Example of solar-powered borehole scheme in Mbare, Zimbabwe*

CONCLUSION

Water-Share Ireland continues to demonstrate how targeted technical expertise, strong partnerships, and focused investment can significantly improve water and sanitation services in some of the world's most vulnerable communities. From delivering safe drinking water to communities in Uganda, critical sanitation infrastructure in Freetown, strengthening systems

in northwest Syria and piloting new water kiosks in Zimbabwe, the partnership is delivering practical, scalable solutions. These projects show the value of combining local knowledge with specialised support from the Irish water sector, helping GOAL and its partners build more reliable, resilient, and sustainable services. As Water-Share grows, its work will remain centred on improving water security, protecting public health, and supporting long-term community resilience.

THE POWER OF A MAP: TRANSLATING GROUNDWATER DATA TO DECISIONS *(2026 BURDON LECTURE)*

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ABSTRACT

Maps are powerful tools for communicating complex concepts, such as hydrogeology, to a range of audiences, from technical specialists to policy and decision-makers and the general public. This paper summarises groundwater mapping activities undertaken by the British Geological Survey and partners over the last 15 years, including ongoing work, with a particular focus on Africa. It provides some background to the evolution of mapping methodologies across different scales (continental, regional, national and sub-national), examining their application by different types of end-users. The paper demonstrates the impact of hydrogeological maps in terms of translating, often sparse and uncertain, groundwater data into appropriate information to make defendable decisions within an African context.

Key words: *hydrogeological mapping, data, decision-making.*

INTRODUCTION

Hydrogeological maps are essential tools for summarising groundwater data and information, helping to demystify an otherwise invisible resource. Hydrogeological maps evolved from geological mapping in the late 1800s, but started to receive increased attention in the mid 20th century as demand for water increased in many industrialised nations. National scale hydrogeological mapping became the focus of national policies to underpin strategic planning for water resources. In Africa, the earliest groundwater maps were published in the 1950s (Struckmeier, 2008). The International Association of Hydrogeologists (IAH) Commission for Hydrogeological Maps was established in 1959, developing the first standardised legend in 1963 in collaboration with UNESCO and FAO. Systematic national hydrogeological mapping was undertaken in the UK in the 1970s and 1980s and the first global scale hydrogeological map was produced in 1999 by the World-wide Hydrological Mapping and Assessment Programme (WHYMAP).

Maps at different scales are designed and suitable for different uses. Traditional hydrogeological maps are generally based on some form of geological classification with a degree of hydrogeological interpretation to show the potential productivity of an aquifer. Thematic hydrogeology maps will focus on a particular aspect of groundwater, such as vulnerability to contamination or drought. Catchment-scale mapping may be applied to site an individual borehole, while national-scale maps play an important role in water resource planning.

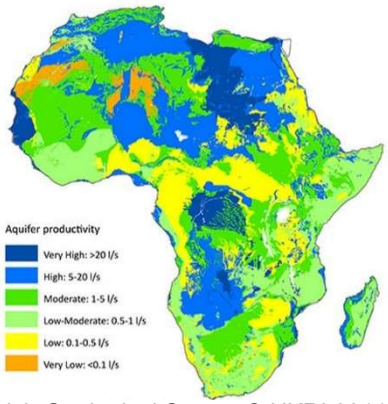
The first quantitative continental-scale groundwater maps of Africa were produced by the British Geological Survey in 2012 (MacDonald et al., 2012). These maps have had widespread impact, catalysing funding for major groundwater projects and research, including development of the Africa Groundwater Atlas (https://africagroundwateratlas.org/). This online resource provides consistent national-scale groundwater maps for almost every country in Africa, which have been downloaded by >11,000 users since their first release in 2019. A new methodology to characterise and map basement aquifers, which underlie ~40% of sub-Saharan Africa, is ongoing and underpinning the development of national and sub-national scale maps for water resource planning, under major groundwater investments such as the World Bank's Horn of Africa Groundwater for Resilience Programme.

This paper summarises these key hydrogeology mapping initiatives, examining the evolution of methodologies across different scales and examining their application by different types of end-users.

CONTINENTAL SCALE GROUNDWATER MAPPING IN AFRICA

QUANTITATIVE MAPS OF GROUNDWATER RESOURCES

Continental-scale maps of groundwater storage, aquifer productivity and depth to groundwater presented the first quantitative assessments of groundwater availability at this scale for Africa (MacDonald et al, 2012). They highlight spatial variations in the distribution of groundwater, but significant potential for groundwater to support widespread abstraction through relatively low-yielding handpumps and to sustain abstraction through short-term variations in annual recharge (Figure 1).



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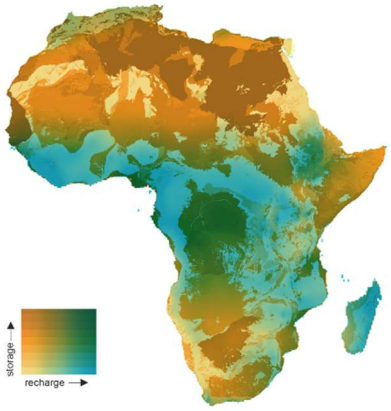
(a) Aquifer Productivity



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(b) Groundwater recharge and storage

Figure 1: *Quantitative maps of groundwater resources in Africa (MacDonald et al., 2012, 2021).*

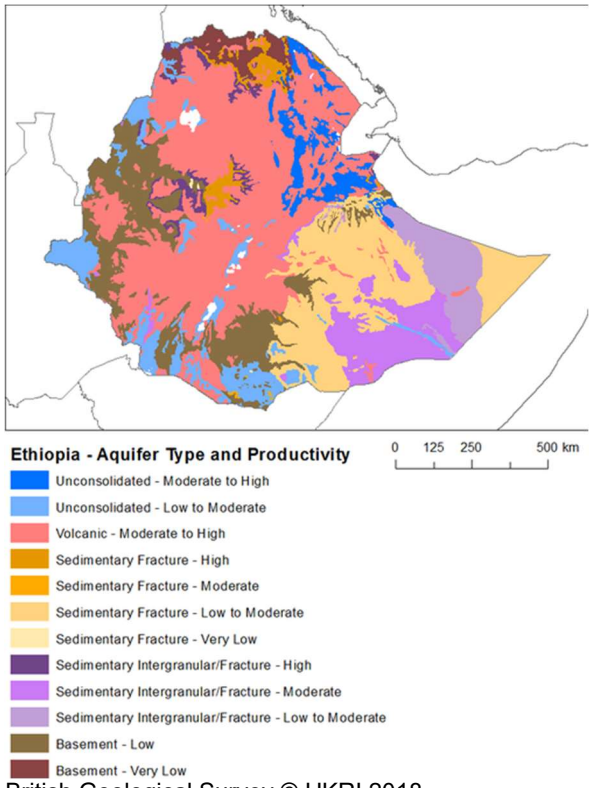
The maps are based on the UNESCO 1:5 million scale geological map of Africa (Furon & Lombard, 1964; Persits et al., 2002). This map was modified based on a systematic review of existing national scale hydrogeology maps, published literature and grey literature. The geological base map was parameterised for aquifer productivity using borehole yields as a proxy, which are much more widely reported than transmissivity data. Aquifer storage was estimated from saturated aquifer thickness and effective porosity, which was defined for each flow/storage type on the geological base map. The maps were reviewed by regional experts, which was a critical step in their production.

A follow-on map of groundwater recharge for Africa (MacDonald et al, 2021) allowed the first continental-scale assessment of groundwater-related water security (Figure 1b). This highlights areas of relatively high and low water security where recharge and storage are both respectively high and low, but also those areas with low recharge and high storage, where storage can help buffer short-term rainfall variability, and areas of low storage that experience reliable recharge.

This suite of maps has been widely cited by a range of high-profile users, including the UN (United Nations, 2022), World Bank (Srivastava et al., 2024), FAO (Flammini et al., 2014), African Ministers' Council on Water (AMCOW, 2022), and WaterAid (Ford et al., 2022) to highlight the potential for groundwater to support socio-economic development in sub-Saharan Africa. A summary of the use metrics for these maps is shown in Table 1. The maps also played a critical role in the decision by the UK Department for International Development (now FCDO) to invest £12M into the UPGro Programme (Unlocking the Potential of Groundwater for Poor). This seven-year research programme was focused on improving the evidence base around groundwater availability and management in sub-Saharan Africa and involved >130 researchers from 43 organisations across Africa and Europe.

Table 1 *Metrics of the 2012 Quantitative maps of groundwater resources*

	Continental quantitative maps (2012)	Continental recharge map (2021)
Publication / map downloads	>165,000	>25,000
Academic citations	587	140
News article citations	18	21
Policy citations	8	1



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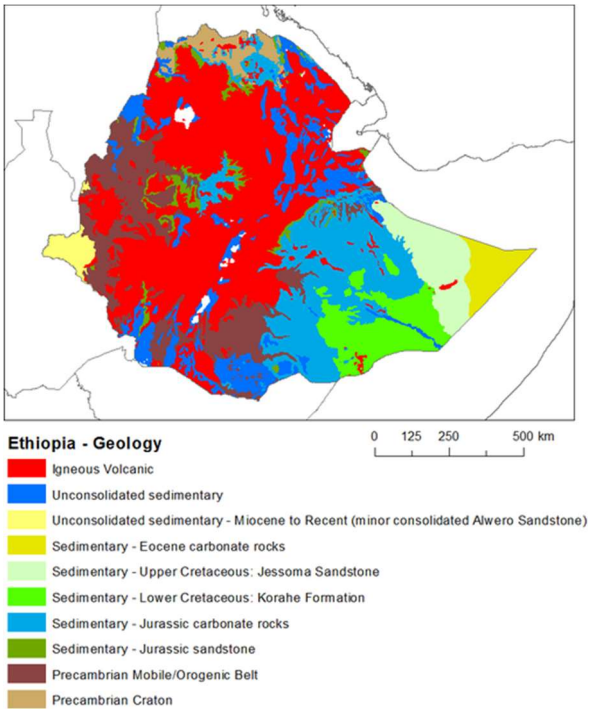

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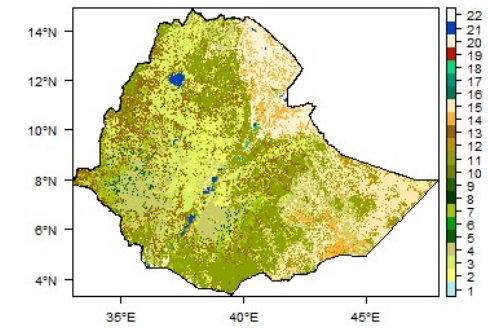

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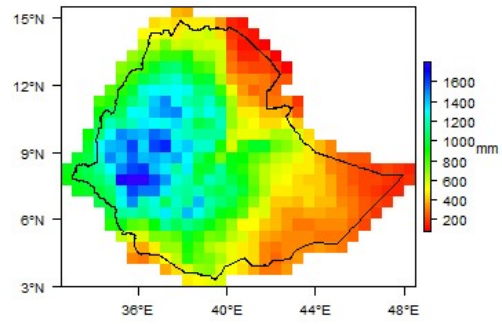


British Geological Survey © UKRI 2018
(d)

Figure 2: *Africa Groundwater Atlas, Ethiopia country page, brings together information on (a) hydrogeology, (b) geology, (c) landuse, and (d) climate (precipitation), alongside soil, surface water, policy/regulation, and the key institutions responsible for groundwater. (Hydrogeology of Ethiopia - MediaWiki)*

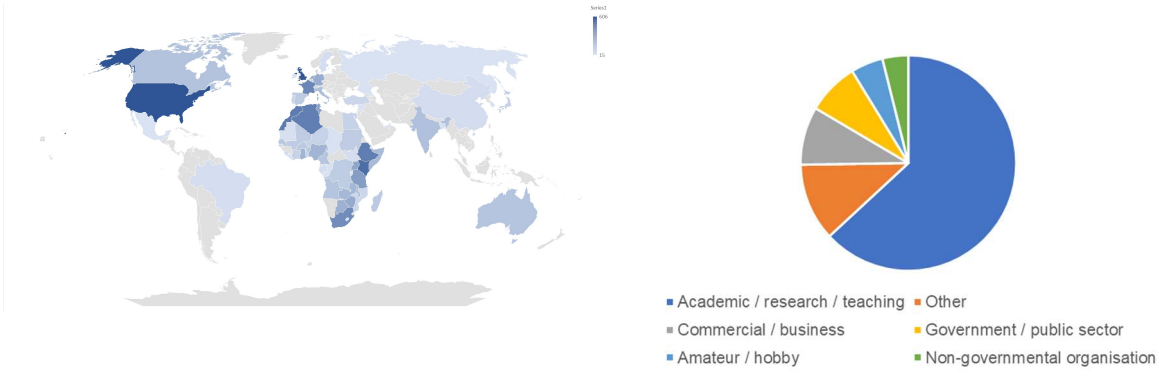
Africa Groundwater Atlas

The Africa Groundwater Atlas was developed as part of the UPGro Programme to improve the availability and accessibility of high-quality information on groundwater in Africa, to support the safe and sustainable development and use of groundwater resources. The Atlas provides

a summary of the hydrogeology and groundwater resources of 51 African countries, acting as a gateway to further information. It was developed in partnership with 64 in-country hydrogeologists, largely through the network of the IAH.

Country-scale geology and hydrogeology maps, combining aquifer type and productivity at a nominal scale of 1:5M, are released for 43 countries. These are available to download as GIS shapefiles. The maps were adapted from the 2012 quantitative maps, working in collaboration with our in-country partners to reflect geological/hydrogeological understanding and nomenclature at a country level. The Atlas also provides supporting information on groundwater-related issues such as monitoring and data, groundwater exploration, and drilling.

The Africa Groundwater Atlas is a widely-used resource. The home-page consistently receives >500 hits per month and the majority of country pages (38) receive >200 hits per month. The country geology and hydrogeology maps have been downloaded by >11,000 users from across the world since their release in 2019 (Figure 3a). The majority of use (~60%) is for academic, research and teaching purposes, but the maps are also used for commercial activities and by government and NGOs (Figure 3b). When users download the maps, they can provide more detail on the intended use of the maps – some examples are provided in Table 2.



(a) Country of user

(b) Reason for use

Figure 3: *User information for the downloadable country maps of the Africa Groundwater Atlas*

FOCUSSING ON THE BASEMENT

Basement aquifers underlie a significant area of sub-Saharan Africa, consisting of complex weathered and fractured crystalline rocks. They are generally low-yielding – capable of supporting small, hand-pump supplies – however there are examples of basement aquifers supporting well fields which can supply towns or larger-scale agricultural activities. BGS is developing a methodology to better quantify the productivity of basement aquifers, providing increased resolution and nuance to the continental-scale maps described above. This methodology is based on a new approach to characterising basement typologies, which considers the nature and depth of weathering and fracturing as controlled by a range of geological, climatic, and landscape factors. These typologies are parameterised based on aquifer thickness, permeability, depth to water table, and borehole yields or transmissivity using available data – some of which was collected during the UPGro Programme. The conceptualisation of basement typologies is used to generate stochastic parameterisations of a radial flow model, which can then be used to assess the probability distribution of borehole yields for each typology. This moves towards a more quantitative approach to defining the likely yield of complex basement aquifers, which can inform investment decisions for different types of groundwater use. The methodology has been applied to West Africa (Bianchi et al, 2023), informing regional groundwater mapping for the ECOWAS (Economic Community of

West African States) region (BGR et al., 2022). It is now being applied at a continental scale to develop a new map of the productivity of basement aquifers in Africa (in prep).

Table 2: *Examples of use of the Africa Groundwater Atlas*

Academic / research / teaching	Identify optimal implementation sites for Photovoltaic Water pumping Research on the impact of climate change on groundwater of Africa Researching groundwater access, contamination, and droughts in relation to elephant deaths, migration patterns Geological information to draw geothermal potential Economics research Research on the potential market size for solar-powered irrigation Enhancement of agriculture sustainability for food security
Commercial / business	To understand geology features so as to map out surface facility developments The data is required for a Sanitation Project for 4 coastal towns for the Government of Angola financed by the African Development Bank. We are considering a larger commercial farming operation in Botswana
Government / public sector	For water resources master plan in Burkina Faso To implement public health project To make regulatory decision to enhance water management in Gambia Mapping for railway project To aid policy and intervention during planning in water for agriculture
NGO	Disaster risk reduction To support studies for solar pumping in boreholes To identify reforestation zones We wanted to dig a borehole on our community farm Conducting research on behalf of the Kalahari Conservation Society WASH coordinator for a humanitarian NGO Assistance to the design of a food security project in Burkina Faso; potential use of groundwater

NATIONAL & SUB-NATIONAL MAPS FOR WATER RESOURCE PLANNING

The typology approach is also being extended and applied to national and sub-national groundwater mapping initiatives in East Africa. This includes the World Bank's Horn of Africa Groundwater for Resilience Programme, UNICEF's More Water More Life Programme, and a BGR-funded project which aims to develop a groundwater decision-support tool for Africa, with a national-scale pilot in Kenya in collaboration with the Water Resources Authority (WRA). Typologies are being developed across the broad spectrum of geological/hydrogeological conditions found in Kenya, which includes basement, volcanics, sedimentary basins, and superficial deposits. These typologies will be parameterised using groundwater data from more than 20,000 boreholes, compiled within the WRA's newly created Groundwater Information System. The maps, which will summarise groundwater potential and risks at a national scale, will provide an important tool to enable more robust groundwater management decisions by the regulator, and to inform investment decisions for those looking to develop groundwater for drinking water or productive/economic uses.

CONCLUSIONS

Groundwater mapping has a long history in Africa. Over the last 15 years, BGS, working in collaboration with partners, has advanced mapping approaches that improve our understanding of groundwater resources across multiple scales. Continental mapping initiatives have helped shape the narrative of the potential for groundwater to support socio-economic development and have made groundwater information more available and accessible to a wide range of users – both technical experts and non-specialists. Methodological development is transforming the way we consider basement aquifers in Africa, providing probabilistic assessments of groundwater yield, which have the potential to inform more robust investment decisions. This evolving methodology is also being applied in

partnership with national governments and authorities to develop national and sub-national scale maps that can inform better management decisions for future groundwater use.

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SESSION V

TFA – THE EMERGING LITTLE PFAS RAISING SOME BIG QUESTIONS

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ABSTRACT

Trifluoroacetic acid (TFA) is an ultrashort PFAS gaining increasing attention globally. TFA is not 'just another PFAS' added to the laboratory target list. It is raising questions and challenges unlike any other PFAS, relevant to regulators and practitioners.

People have only recently started to analyse for TFA, and where it is tested for it is notable not just for its ubiquity – test for it and you will probably find it – but also its concentration, often two orders of magnitude higher than other PFAS. Atmospheric persistence and global dispersion means it can travel thousands of kilometres from its point of origin. Where regulations have been written for 'total PFAS' with thresholds set to be protective of risks from long chain PFAS such as PFOS, testing for TFA may trigger exceedance from ambient PFAS even at locations remote from a contaminant source site.

In this paper we bring together some key aspects of our current understanding of TFA in the environment, how they challenge our current approach to managing PFAS, and how this may impact future actions. Topics to be covered will include definition; detection; sources; occurrence in environmental media and the food chain; evidence for toxicity and bioaccumulation; and regulatory approaches.

Key words: *TFA, PFAS, Emerging Contaminants.*

WHAT IS TFA?

DESCRIPTION

TFA is short for Trifluoracetic Acid (CF_3-COOH, CAS No 75-0501), Figure 1. It comprises one fully fluorinated carbon and a carboxylic acid functional group, making it the shortest perfluoralkyl carboxylic acid and the smallest member of the family of PFAS (per- and polyfluoroalkyl substances). It is a very strong acid and therefore exists in water in its anionic form, trifluoroacetate (CF_3-COO^-). Its polarity means that it partitions or dissolves readily into the aqueous phase, both in the atmosphere and in terrestrial and aquatic environments. TFA which partitions into water droplets in the atmosphere can be deposited through wet deposition as rain or snow.

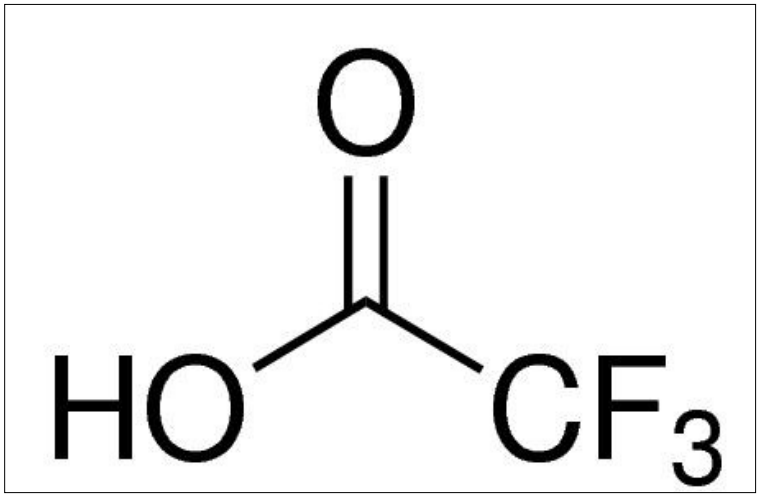

Figure 20: *Molecular structure of TFA.*

DEFINITION AS PFAS

Global opinions differ as to whether TFA should be considered as a PFAS but the widely accepted definition from the Organisation for Economic Co-operation and Development (OECD, 2021) clearly recognises TFA as a PFAS. In contrast, the United States Environmental Protection Agency (US EPA) has adopted a narrower working definition of PFAS that excludes TFA (US EPA, 2025a).

TFA is included within the scope of the universal PFAS restriction currently being considered by the European Chemical Agency (ECHA, 2026).

ANALYSIS

The analysis of TFA in environmental samples is challenging because of its high polarity, low molecular weight, and strong acidity (Moscato et al., 2025). Its low molecular weight leads to poor retention and early elution in conventional reversed-phase LC-MS/MS (liquid chromatography–tandem mass spectrometry) methods commonly used for PFAS analysis, and also results in reduced ionisation efficiency, complicating trace-level detection in complex matrices. Evaporative losses may occur during sample preparation resulting in variable recoveries. It is not simply another target PFAS which can be added to the monitoring suite if a reference standard is available. Commercial laboratories need time to develop and validate robust monitoring methodologies.

TOXICITY

There is no universal agreement on the potential health effects of TFA, although it is understood that the World Health Organisation (WHO) is currently assessing this. As discussed by Arp et al. (2024) it was previously suggested that the hazard related concerns of TFA and other short-chain PFAS are much lower than those of long chain PFAS which were found to be more bioaccumulative and more toxic. Limited toxicological studies have been undertaken, however there are indications from mammalian toxicity studies that TFA is toxic to reproduction and that it exhibits liver toxicity. Ecotoxicity data are scarce, with most data being for aquatic systems and fewer data available for terrestrial plants, where TFA bioaccumulates most readily. In May 2025 the European Chemicals Agency (ECHA) opened a consultation on classifying TFA as a reprotoxic, and PMT (persistent, mobile and toxic) and vPvM (very persistent and very mobile) substance. The German Environment Agency (UBA 2021) have used data including from chronic rat toxicity studies to develop a Tolerable Daily Intake of 0.018 mg/kg bw/day.

WHERE TFA COMES FROM

TFA is used as a substance in chemical manufacturing, and can also be formed as a transformation product from any chemical with a C-CF_3 group. These include chemicals discharged into the environment in large quantities during their application including refrigerants and other F-gases, plant protection products, pharmaceuticals and biocides (UBA, 2021).

The German Environment Agency (UBA, 2024) published estimates for TFA emissions from sources in Germany suggesting that refrigerants and blowing agents were the largest quantifiable source of TFA at ~2000 t/year, ~457 t/year pesticides and ~29 t/year human pharmaceuticals.

TFA can also be formed through incineration of wastes containing PFAS, and as a degradation product within landfills. TFA in the atmosphere can be transported for hundreds of kilometres and also partitions into water droplets and is deposited through wet deposition as rain or snow.

It has been suggested that TFA can form naturally, associated with deep sea hydrothermal vents, however recent studies such as Joudan et al. (2021) suggest there is insufficient evidence for this hypothesis or reasonable mechanism of formation. Even if TFA is formed

naturally, the contribution of natural sources to the planetary burden is far outweighed by anthropogenic sources.

TFA FROM F-GASES

A major source of TFA is the atmospheric degradation of volatile fluorinated compounds (F-gases) used as refrigerants and in manufacturing (Arp et al., 2024). This includes hydrochlorofluorocarbons (HCFCs), saturated hydrofluorocarbons (HFCs), and unsaturated hydrofluoroolefins (HFOs). HCFCs and HFCs are greenhouse gases, restricted under the Montreal Protocol, and they are being increasingly replaced by HFOs, which have shorter atmospheric lifetimes resulting in lower greenhouse effects. Unfortunately, HFOs degrade in the atmosphere to TFA, with a much higher yield than the greenhouse gases they replace. This is resulting in a rapidly increasing burden of TFA deposition - modelling studies have suggested that that TFA concentrations in precipitation will increase by a factor of 10 to 100 in major HFO source regions compared to levels forecasted from HFC degradation or previously observed (Henne et al., 2025).

TFA IN INDUSTRIAL PRODUCTION

TFA is used directly in some chemical manufacturing, and is registered under REACH as manufactured and/or imported into the EU in volumes ranging from 100 to 1000 t/year, although use is likely to decline. Investigation by a non-governmental organisation (NGO) of surface water in the vicinity of a TFA manufacturing facility in France found concentrations of up to 7500 µg/L TFA (Generations Futures, 2024). The chemical manufacturer has since decided to stop production at the plant, and also at another plant producing TFA in Germany (Solvay, n.d.).

TFA FROM PESTICIDES AND OTHER PLANT PROTECTION PRODUCTS

Pesticides can be a substantial source of TFA to the environment and water sources (Joerss et al., 2024). Many plant protection products contain a -CF3 group, with the potential to have breakdown products including TFA. The Danish Environmental Protection Agency (Miljostyrelsen, 2024) investigated seven organofluorine pesticides widely used in Denmark. The study showed that all could be converted to TFA, although the TFA formation varied between pesticide and in different soil conditions, with the amount of TFA generated sufficient to affect underlying groundwater quality, albeit below the drinking water quality standard. Similar results have been reported in Germany, where studies showed a significant increase in TFA in groundwater concentrations from agriculture compared to other uses (Joerss et al.., 2024). Plant treatment products are considered to be a major non-atmospheric source of TFA to the environment (Henne et al., 2025).

A different approach is taken to TFA-precursor pesticides in the United States. US EPA has stated "*EPA-approved single fluorinated compounds are not forever chemicals, they are not PFAS, and do not pose any risks of concern when used as labeled*." (US EPA, 2025b).

TFA FROM PHARMACEUTICALS

Many pharmaceuticals also contain -CF3 groups and are therefore likely precursors of TFA. These are most likely to enter the water environment through waste and waste water including discharge from waste water treatment works.

TFA FROM WASTE – LANDFILLS AND INCINERATORS AND WASTE WATER TREATMENT

TFA may be present in waste emissions, derived from precursors in the received waste.

The C-F bonds in PFAS are very strong, and thermal destruction by high temperature incineration in optimised conditions at least 1,100°C is recognised as one of the few available destructive treatments for PFAS-containing materials such as fire fighting foam concentrate and fluoropolymers (Environment Agency, 2025). However, TFA may be formed where incineration takes place in less optimal conditions, where there is incomplete combustion and

emission of products of incomplete combustion (PICs). According to studies referred to by the Environment Agency (2025), heating PTFE (polytetrafluoroethylene) between 250°C and 600°C, particularly under uncontrolled conditions, can generate PFCAs (perfluorocarboxylic acids) and other short chain fluorinated compounds including TFA. Further research is required to better understand the prevalence and contribution of TFA from general incineration of municipal and other wastes including incidental PFAS-containing materials.

Unsurprisingly, the limited studies of TFA associated with landfills also indicate the presence of TFA both in leachate and in landfill gas emissions (Wang et al., 2020). TFA is likely to be released in landfills through the degradation of precursors with a -CF3 group, including pesticides and pharmaceuticals.

Municipal wastewater treatment plants are also a source of TFA into the aquatic environment, through the presence of TFA precursors and because TFA is not removed during wastewater treatment (UBA, 2023)

TFA REGULATION

As discussed above, TFA is defined as a PFAS under the OECD definition (OECD, 2021) which is adopted in much of the world, including UK and Europe (but not the USA). PFAS are a complex family of chemicals which are challenging to regulate individually and therefore jurisdictions are looking to regulate PFAS as a single class, both for restrictions and also for developing acceptability criteria (Bowles et al., 2024). The inclusion of TFA introduces new challenges to this approach, in particular due to its ubiquity and prevalence at concentrations orders of magnitude higher than the more-studied PFAS such as perfluoroctane sulfonic acid (PFOS). As explored by Kramer et al. (2026), regulating TFA is particularly challenging because its numerous sources, extreme persistence, and global mobility create significant uncertainties about its risks and how best to manage them. These characteristics also disperse regulatory responsibilities across sectors and jurisdictions, allowing different organisations to influence how risks and uncertainties are interpreted and addressed, ultimately shaping regulatory outcomes.

INCLUSION IN EU ENVIRONMENTAL QUALITY STANDARDS

In February 2026, the EU issued the formal directive introducing revised EQS, including a new EQS for the sum of 25 PFAS (Council of the European Union, 2026). Member states will need to transpose the directive into local legislation by the end of 2027, and the new EQS need to be complied with by 2035.

The list of PFAS in the EQS includes 24 long and short chain PFAS which were first proposed for inclusion in a revised EQS several years ago, and TFA, which was only added to the list in the last year. The EQS has been set as 4.4 ng/L for the sum of 25 PFAS ‘as PFOA equivalents’ with relative potency factors (RPFs) set for each of the 25 PFAS. This means that the analytical result for each individual PFAS is multiplied by the RPF before they are added together to make the sum of PFAS as PFOA equivalents. PFOS has an RPF of 2, while TFA has an RPF of 0.002. This means that 2 ng/L PFOS is equivalent to 1 ng/L PFOA, and 500 ng/L TFA (0.5 µg/L) is equivalent to 1 ng/L PFOA. This low RPF recognises the relatively low expected toxicity of TFA.

TFA IN THE EU DRINKING WATER DIRECTIVE

The EU Drinking Water Directive (EU, 2020) sets two separate PFAS parameters that Member States must monitor in drinking water, a ‘Sum of PFAS’ (PFAS-20) of 0.1 µg/L (implemented in 2026) and a ‘PFAS Total’ of 0.5 µg/L. The ‘PFAS Total’ parameter covers all PFAS present, but requires confirmation of a harmonised monitoring method prior to full implementation.

In 2024 the EU published a Commission Notice with technical guidelines for methods of analysis for monitoring in drinking water (OJEU, 2024) in water intended for human consumption, including ‘Sum of PFAS’ and ‘PFAS Total’. This acknowledges that OECD definition of PFAS has been updated since the Drinking Water Directive was issued, and that

TFA is now included in the definition of 'PFAS Total'. It also acknowledges that available TFA monitoring results from raw water sources in the EU indicate that TFA concentrations at the point of compliance may significantly exceed the Directive's 'PFAS Total' parametric value. It also refers to the ongoing WHO health impact assessment and uncertainty of TFA toxicity. It therefore recommends that when analysing for 'PFAS Total', the analyst should also determine the TFA in the sample, and report as PFAS Total, TFA, and PFAS Total – TFA. The notice does not detail any action to be taken in case of exceedances.

OTHER DRINKING WATER STANDARDS FOR TFA

Some EU countries have already adopted their own drinking water guidance for TFA. In Germany, the German Environment Agency (UBA, 2021) have published a drinking water guidance value of 60 µg/L, derived from the TDI they derived, however the guidance emphasises that the concentration in drinking water should be kept as low as reasonably possible and a value of 10 µg/L should be targeted.

In the Netherlands an indicative drinking water value of 2.2 µg/L has been developed based on the potency factor relative to perfluorooctanoic acid (PFOA) and its threshold for drinking water.

WHY IS TFA OF EMERGING INTEREST TO HYDROGEOLOGISTS NOW ?

The strength of the carbon-fluorine bond means that, like other PFAS, TFA is very persistent. It is also very mobile, not just in the terrestrial water environment, but also through atmospheric dispersion of aerial emissions. While long chain PFAS from the use of fluorinated fire fighting foam have been shown to persist in groundwater and rivers for tens of kilometres downstream from source zones (Coffey Australia Pty Ltd., 2018), TFA can be dispersed hundreds of kilometres or more from its point of origin, and be deposited in detectable amounts in precipitation. This, combined with the diversity of potential uses and precursors, leads to the ubiquity of TFA even in what might be expected to be pristine environments (Henne et al.., 2025). As TFA does not generally break down in the environment, continuing use results in an increasing environmental burden, which is clearly visible in long term studies (Arp et al., 2024; Henne et al.; 2025, Albers and Sültenfuss, 2024). Even with restriction on new uses of TFA, it will continue to be present in the environment for decades to come.

The potential for harm resulting from the ubiquity of TFA is the subject of debate (e.g. Kramer et al., 2026). Some such as the European FluoroCarbons Technical Committee (EFCTC, n.d.) argue TFA is a naturally occurring substance with predicted environmental concentrations remaining well below toxicity thresholds. Others such as Arp et al. (2024) argue that, although it may be less toxic than other larger PFAS, the irreversible rise in concentrations of TFA, combined with extreme persistence and ongoing emissions, present a threat to planetary boundaries.

While TFA has been known about for decades (Arp et al., 2024), it has only really been drawing significant interest from hydrogeologists and land contamination specialists in the last year or so. The inclusion of TFA in the new European Union (EU) EQS for the Sum of PFAS (Council of the European Union, 2026) will focus even more attention on this substance as it is included in standard monitoring suites and new data become available.

As more testing for TFA is being reported, its ubiquity is becoming clearer. In the last year a number of studies have been published by NGOs and others, testing TFA in a variety of the environment, drinking water and also beer, wine, and breakfast cereal, resulting in some alarmist headlines in the popular press. It is inevitable as environmental consultants start to test for TFA in accordance with the EQS that it will be found at concentrations exceeding the other PFAS tested for. It is increasingly important that practitioners and regulators recognise the different challenges TFA will bring, and are prepared to manage them in a proportionate manner cognisant of both global and local context, and not treating it as 'just another PFAS'.

TFA OCCURRENCE AND PREVALENCE IN WATER

This combination of persistence and mobility, coupled with multiple and growing sources has led to widespread distribution and accumulation in the environment. As TFA has been increasingly included in monitoring suites, awareness is increasing of its omnipresence and prevalence, not just in surface water, but also in groundwater, in rainfall, and in food and drink. Where it is looked for in monitoring it is usually found, and the concentrations of TFA in environmental media are frequently orders of magnitude higher than other PFAS.

Here we discuss some examples illustrating the occurrence and prevalence of TFA in the environment. Many of these examples are from very recent investigations by NGOs which are limited studies, are not peer-reviewed and merit further investigation. Together they provide an indication not only of the likely scale of TFA occurrence, but also of the rate of increase of TFA in the environment in recent years.

TFA IN DRINKING WATER SOURCES IN GERMANY

The study by Neuwald et al. (2022) drew attention to the abundance and prevalence of TFA in drinking water sources in Germany, when they showed that TFA was the most dominant PFAS, accounting for more than 90% of the total concentration of PFAS analysed in all samples, with a maximum and median concentration of 12.4 and 0.9 µg/L- at least two orders of magnitude higher than any of the EU DWD 20 PFAS.

TFA IN FRENCH DRINKING WATER 2023-2025

The French National Agency for Food, Environmental and Occupational Health Safety (ANSES) published the findings of a national campaign to measure emerging compounds in drinking water, conducted from 2023 to 2025, and from sites covering about one-fifth of France's distributed water. Of the 35 PFAS analysed, 20 were detected in raw water samples and 19 in tap water samples. Some were present in only one sample, while others were found more frequently. Notably TFA was detected in 92% of both raw and tap water samples. Its concentration varied considerably from one sample to another, with a median of 780 ng/L in treated water. The maximum result of 25,000 ng/L was in water taken downstream from a factory that produces TFA.

TFA IN RAINWATER IN THE UNITED STATES

A literature review (Zenobio et al., 2024) of PFAS in precipitation in the United States, found TFA was present in every sample in which it was tested for, with concentrations ranging from 3 to 2400 ng/L (mean 340 ng/L). PFOS was only detected in around half the samples tested, at lower concentrations ranging from 0.06 ng/L to 103 ng/L (mean 8.8 ng/L).

TFA IN SURFACE WATER IN THE UK

In 2025, the NGO Fidra published a study (Fidra, 2025) reporting the results of monitoring TFA concentrations at 54 locations covering 32 rivers across the UK. The study aimed to determine whether TFA was present in UK surface water and to establish the degree of contamination compared to findings in other countries. TFA was detected in 167 of the 214 samples analysed, with TFA being detected on at least one occasion in all but one of the 54 locations sampled. Mean TFA concentrations in most rivers was between 100 ng/L and 1000 ng/L. However, one location on the River Kelvin in Glasgow had substantially higher TFA, up to 78,464 ng/L, skewing the study mean. No explanation is given for this exceptionally high result.

TFA IN GROUNDWATER IN GERMANY AND DENMARK

The occurrence of TFA in groundwater in Germany has been reviewed and mapped by UBA (2024). The maps show widespread occurrence, with concentrations ranging from <0.1 µg/L to > 30 µg/L.

In Denmark, Albers and Sultenfuss (2024), looked at TFA concentrations in 73 groundwater monitoring wells across Denmark, all sampled in 2023. The wells sampled are used for

monitoring only and have negligible influence from groundwater abstraction. TFA was present at the quantification limit (0.03 µg/L) or higher in 70 of the wells, with 1.6 µg/L being the highest concentration measured.

Previous studies by Nielsen et al. (2001) had indicated that TFA was not present in old groundwater, recharged before the middle of the twentieth century. Albers and Sultenfuss (2024) used tritium-helium dating to estimate the year of groundwater recharge to establish long-term trends of TFA in groundwater. They found a clear trend of TFA concentration increasing in groundwater since 1960. TFA was not detected in tritium-free groundwater recharged before 1960, while it was detected at low concentrations in most samples recharged between 1960 and 1980. Groundwater recharged after 1980 had at least 0.1 µg/L TFA, and the concentration increased with time. Shallow groundwater from natural "background" areas revealed some variation of TFA even with diffuse atmospheric deposition as the only source, suggesting local sources must contribute TFA to some of the monitoring wells. They also observed the potential for using TFA as a simple indicator of groundwater age, such as the presence of young water in a groundwater abstraction well.

TFA IN SWITZERLAND

Henne et al. (2025) have published a detailed study of concentrations of TFA observed in precipitation and surface waters in Switzerland during three years of continuous monitoring and in archived water samples, collected since 1984. They used the data, combined with modelling approaches, to attempt source apportionment to understand whether the TFA found in the water environment could be explained by likely sources including F-gases and plant protection products (PPP).

In precipitation, mean observed TFA concentrations ranged from 0.30 to 0.96 µg/L across 14 sites. In surface waters sampled in 2021-2023, TFA ranged from 0.33 to 0.88 µg /L, but demonstrated a four-to-six-fold increase compared to samples collected in 1996/1997.

For the source apportionment, atmospheric deposition of TFA in Switzerland was estimated as 24.5 ± 9.6 Mg yr−1, whereas TFA terrestrial inputs from the degradation of PPP in soils, estimated from the literature, ranged from 2.9 to 11.8 Mg yr−1, depending on the assumption on degradation efficiency. In agricultural areas, TFA inputs from the degradation of PPP were two to three times as much as those from atmospheric depositions. TFA inputs were balanced by exports from Switzerland through the major rivers, 31 ± 4 Mg yr−1.

TFA IN PLANT-BASED FOODSTUFFS

As discussed by Scheurer and Nödler (2021), PFAS transfer from soil to plants depends on chain length, with short-chain PFAS moving more readily into plant tissues. As transpiration is the primary mechanism driving PFAS movement within the soil–plant system, ultrashort-chain PFAAs (perfluoroalkyl acids) such as TFA are expected to accumulate most strongly in plant parts with high transpiration rates, particularly the leaves. Given TFA's widespread presence in rainfall, plants are likely to be continuously exposed to it, even in organic farming systems where pesticides have not been used.

BEER AND TEA

A study by Scheurer and Nödler (2021) shows that TFA is a widely spread contaminant in beer and tea / herbal infusions. In 104 beer samples from 23 countries, TFA was detected up to 51 µg/L with a median concentration of 6.1 µg/L. Experimental studies showed that malt was likely to be the main source of TFA in the beer. They also showed elevated concentrations of TFA in tea and herbal infusions with a median concentration of 2.4 µg/L, with the TFA likely extracted from the leaves in the hot infusion.

CEREALS

In 2025 the NGO Pesticide Action Network Europe published a study on TFA in cereals in Europe (PAN Europe, 2025) triggering sensationalist headlines across popular media such as

"Scientists issue urgent warning about eating CEREAL" (Daily Mail, 5 December 2025). The study found TFA was detected in 81.8% of samples (54 out of 66 samples) across 16 European countries. The average TFA concentration was 78.9 µg/kg, with a median of 39.5 µg/kg and peak values of up to 360 µg/kg. Wheat products contained significantly more TFA than other cereal-based products.

WINE

TFA is also found in wine. The NGO GLOBAL 2000 published a study in 2025 (Global 2000, 2025) detailing the results of testing TFA in wine from various European countries. The study included wines dating back to 1988, providing a record of changes in TFA over time. The study showed an exponential rise in TFA levels in wine since 2010, with TFA not detected in wines from before 1988. Wines from 2021–2024 show average levels of 122 µg/L, with some peaks of over 300 µg/L. Wines from 10 EU countries were analysed. While average TFA levels varied, wines from all countries showed levels of TFA several orders of magnitude higher than background levels in water. Wines with higher levels of TFA were also reported to contain a greater number and quantity of synthetic pesticide residues. However, TFA was also found in organic wines. While this is not a peer reviewed scientific study, it provides a good illustration not only of the potential for TFA to be widespread across the food chain, but also the rapid increase in TFA in the food chain as global practices have changed.

CONCLUSIONS

TFA is rapidly emerging as a PFAS of global concern. Its mobility and persistence, combined with the increasing and widespread use of its precursor chemicals, has resulted in global impact. TFA is now found widespread across the environment and when included in testing suites it is usually the most prevalent PFAS by a couple of orders of magnitude. However, all the indications are that it is less toxic than the better studied PFAS, by a couple of orders of magnitude, and this is reflected in the new EQS.

It is inevitable that as TFA is added to analytical suites and more results are obtained, the analysis will show the presence of TFA at concentrations much higher than practitioners and regulators are used to for PFAS. It is important that the response to this is proportionate, and takes into account the ubiquity of TFA in diffuse sources such as precipitation. This challenges regulatory approaches where the expectation has been for 'all PFAS' to be removed and remediated. It would not be practical nor proportionate to expect removal of all TFA.

Meanwhile, continued use of TFA precursors without any removal or destruction is growing the global load with continuing increase of TFA in the water cycle. TFA continues to increase in rainfall, in groundwater, in the ocean, in food and drink, in wine and in beer and even in tea. As a society we need to better understand the sources and impacts, and whether the benefits we gain are worth the long-term global impacts, and whether more suitable alternatives exist. For example, Denmark has restricted use of certain pesticides. However, action needs to be taken on a global scale – even if one country immediately restricted all use of TFA and its precursors, it would still receive the impacts from global use through atmospheric dispersion, the ocean, and imported food.

And maybe, of some comfort to hydrogeologists, one place you might not find TFA is in old groundwater, and you might even be able to put its occurrence to some use in improving understanding of groundwater age.

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PREDICTING DISINFECTION BYPRODUCT FORMATION IN SMALL DRINKING WATER CATCHMENTS

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ABSTRACT

In Ireland, approximately 82% of public water supplies originate from surface water sources which require chemical disinfection with chlorine to meet microbial drinking water quality standards. The presence of natural dissolved organic matter (DOM) in source waters prior to chlorination can lead to the formation of unwanted and potentially carcinogenic disinfection byproducts (DBPs) such as trihalomethanes (THMs). In recent years, Ireland has had the highest number of exceedances for total trihalomethanes (THM4) in treated drinking water across European Union (EU) member states. This research integrates advanced optical monitoring techniques, namely fluorescence excitation–emission matrix (EEM) spectroscopy combined with parallel factor analysis (PARAFAC) and machine learning (ML) techniques to better understand, predict, and manage DBP formation potential. Surface water and groundwater samples from two small drinking water catchments were subject to laboratory chlorination under standardised, uniform formation conditions. The study demonstrates that EEM-PARAFAC components are highly selective predictive variables for DBP formation and when combined with ML tools, may offer a promising way forward for real time DBP forecasting applications. Furthermore, spatial analysis reveals a strong influence of landcover characteristics on DBP precursor dynamics, with peatland and forested areas identified as high-risk zones. The findings will support the development of new online monitoring technologies with opportunities for improved water treatment optimisation and proactive source protection strategies.

Key words: *Disinfection byproducts, trihalomethanes, fluorescence spectroscopy, dissolved organic matter, drinking water.*

INTRODUCTION

Ireland's drinking water is heavily dependent on surface water sources, accounting for approximately 82% of public water supplies which require disinfection with chlorine to inactivate pathogens and prevent the spread of waterborne diseases. Chlorination is invariably associated with the unintended formation of potentially harmful DBPs, such as THMs and haloacetic acids (HAAs), through reactions with native DOM and inorganic ions (e.g., Br) naturally present in raw water sources. Long term exposure to excessive THMs in drinking water has been linked to increased risk of bladder cancer (e.g., Evlampidou et al., 2020). In recent years, Ireland has reported some of the highest rates of THM4 exceedances of drinking water regulatory limits for public water supplies in the EU (O'Driscoll et al., 2018). Given that THMs are just one prominent class of over 1,400 known DBPs reported to date with many more non-target compounds yet to be identified (Chen et al., 2014), it is likely that the present public health risk from drinking water exposure to DBPs is currently being significantly underestimated in Ireland and around the world.

Raw water DOM is a complex mixture of reduced organic carbon and nitrogen compounds derived from both terrestrial (allochthonous) and in-stream (autochthonous) sources. In upland peatland and forested catchments, DOM is typically dominated by humic substances, which

are highly reactive during chlorination. In contrast, agricultural and microbial sources contribute more labile, protein-like organic matter, which can influence the formation of nitrogen-containing DBPs which are unregulated and potentially more cytotoxic and mutagenic. Traditional precursor monitoring tools, such as dissolved organic carbon (DOC) and UV absorbance at 254 nm (A_{254}), provide only limited information on DOM composition and may not adequately capture the molecular complexity of precursors involved in DBP formation. Advances in UV-vis spectroscopic techniques, such as EEM-PARAFAC have enabled detailed molecular characterisation of fluorescent DOM (FDOM) components linked to DBP formation during water treatment worldwide (Fernandez-Pascual et al., 2023). The overall goal of the present study was to better understand the role of FDOM in the formation of regulated DBPs (THMs and HAAs) as well as priority emerging DBPs such as dichloroacetonitrile (DCAN), trichloronitromethane (TCNM), and trichloropropanone (TCP) at sub-catchment scale in Ireland. The research aimed to demonstrate the application of ML techniques in prediction of DBP formation from raw water hydrochemical and FDOM measurements to help provide practical solutions drinking water quality management.

MATERIALS AND METHODS

Two small drinking water sub-catchments in the River Lee basin (draining areas of 17km^2 and 35km^2) with a history of elevated THMs in treated water were selected for a high-resolution spatiotemporal surface water (n = 24) and groundwater (n = 11) sampling programme. The smaller catchment (River Bunsheelin) is characterised by thin peaty soils with steep slopes and mountainous topography whereas the larger basin (River Dripsey) has lower relief with improved grassland in lowland agricultural areas. Both study areas are representative of the general physiography of small Irish drinking water catchments subject to recurring THM4 exceedances, which typically feature peaty soils in upland headwater tributaries which transition to lowland agricultural pasture (O'Driscoll et al., 2018).

Laboratory chlorination experiments were conducted on pre-filtered (<0.7 µm) surface water and groundwater samples under uniform laboratory conditions (pH 7, 25 °C for 72 hours in darkness) with a single 5/1 excess Cl_2/DOC dose. Eighteen DBP parameters were considered namely trichloromethane (TCM), bromodichloromethane (BDCM), dibromochloromethane (DBCM), tribromomethane (TBM), THM4, monochloroacetic acid (MCAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), monobromoacetic acid (MBAA), dibromoacetic acid (DBAA), HAA5, trichloroacetonitrile (TCAN), DCAN, bromochloroacetonitrile (BCAN), dibromoacetonitrile (DBAN), TCNM (chloropicrin), dichloropropanone (DCP) and TCP. Hydrochemical parameters and DOM spectroscopic properties were measured on source waters prior to chlorination with PARAFAC applied to decompose the EEMs into the independent underlying FDOM components present in each sample. Two independent ML models were developed from source water sample spectroscopic and hydrochemical measurements (n = 198) as candidate predictive variables for DBP formation. Models included neural networks (NNET), bagging tree techniques (BAG) and a generalised boosted regression model (GBM) with binary presence-absence classification using a support vector machine (SVM). The first model considered the optimal number of predictive variables from a systematic selection procedure (Droz et al., 2025). A second independent ML model was trained under the same workflow using DOM spectroscopic measurements alone with a view towards real time online monitoring applications at drinking water treatment plants.

RESULTS

The overall concentration ranges of the DBP parameters considered under the experimental conditions of the present study are presented in Table 1 where source water DOC concentrations ranged from 0.5 to 16 mg L^{-1}. THMs were dominated by chloroform (TCM) = 245 (± 283 µg L^{-1}) with HAAs dominated by TCAA = 6.8 (± 9.4 µg) and DCAA = 5.1 (± 4.6 µg L^{-1}). Priority emerging DBPs were present in over 85% of samples including DCAN = 2.6 (± 1.2 µg L^{-1}), TCNM = 1.7 (± 2.2 µg L^{-1}) and TCP = 4.0 (± 2.5 µg L^{-1}).

Table 1: *DBP formation concentrations under conditions of the present study (n = 198)*

Disinfection byproduct	Range (min-max)	Mean	Occurrence (%)
Trihalomethanes (THMs)			
TCM (µg L^{-1})	1.55 – 2132	234.71	100
BDCM (µg L^{-1})	<LQ – 101.39	27.86	92.8
DBCM (µg L^{-1})	<LQ – 55.37	4.42	78.9
TBM (µg L^{-1})	<LQ – 9.87	0.28	7.1
THM4 (µg L^{-1})	1.55 – 2159.12	267.43	100
Haloacetic acids (HAAs)			
DCAA (µg L^{-1})	<LQ – 28.60	5.07	97.1
TCAA (µg L^{-1})	<LQ – 64.16	6.82	94.9
HAA5 (µg L^{-1})	1.00 – 91.19	12.13	100
Haloacetonitriles (HANs)			
TCAN (µg L^{-1})	<LQ – 4.16	0.10	24.5
DCAN (µg L^{-1})	<LQ – 9.37	2.61	98.6
BCAN (µg L^{-1})	<LQ – 4.25	0.61	42.4
DBAN (µg L^{-1})	<LQ – 2.8	0.19	16.2
Halonitromethanes (HNMs)			
TCNM (µg L^{-1})	<LQ – 24.19	1.61	87.5
Haloketones (HKs)			
DCP (µg L^{-1})	<LQ – 5.54	0.17	11.3
TCP (µg L^{-1})	<LQ – 22.96	3.89	99.4

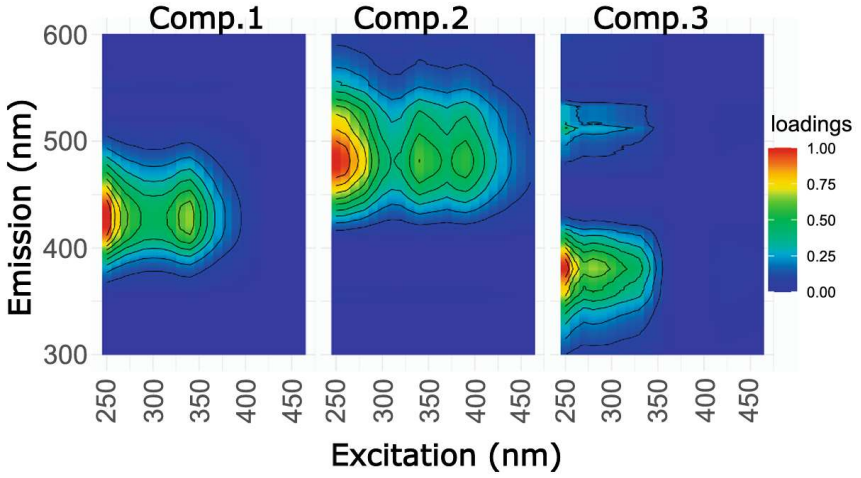

Figure 1: *PARAFAC model results showing components C1 to C3 loadings which represent the individual fluorophores present in source water (from Droz et al., 2025).*

A six-component PARAFAC model was derived from EEM spectra with the first three components (C1 to C3) comprising 98 % of model variable importance (Figure 1). Components C1 and C2 are frequently reported terrestrially derived (allochthonous) humic-like fluorophores which are widely described in the literature in freshwater environments. Component C3 is a tryptophan-like fluorophore representing low molecular weight proteinaceous and nitrogenous DOM which is also well documented in the literature. Similar components have been reported previously in Irish surface water (O'Driscoll et al., 2018). Ten source water variables, namely DIC, DOC, NH_4, DON and Br concentrations, the humification index (HIX), PARAFAC components C1 to C3 and the proportion of the component C3 relative to the sum of the component C1 to C6 (% C3), were determined to be the optimised combination of variables for predictive modelling (Droz et al., 2025).

Of the DBP parameters investigated, the frequency of detection for TBM, TCAN, BCAN, DBAN and DCP detections was very low (Table 1). Hence, for these compounds only binary presence-absence SVM models were trained. The average performance on the training dataset was excellent for presence (SVM accuracy = 96.8 ± 3.0 %) and very good for quantitative prediction (R^2 = 0.83 ± 0.06, precision = 12.6 ± 2.6 %, root mean squared percent error = 29.0 ± 9.9 %) of DBPs. Ten DBP parameter concentrations, namely THM4, HAA5, TCM (chloroform), BDCM, DBCM, DCAA, TCAA, DCAN, TCNM (chloropicrin) and TCP could be accurately predicted (Figure 2) (average R^2 = 0.86, root mean squared percent error = 27.9 %). BAG and GBM demonstrated similar performance and NNET over performed for all DBPs. Reasons for the over performance of NNET models is not immediately clear, however it could be hypothesised that NNET models have a stronger tendency to capture complex non-linear relationships between features. DBP formation prediction performed best (e.g., $R^2 \geq 0.7$) for regulated DBPs such as TCM, THM4, DCAA, TCAA and HAA5 with lower values for BDCM and DBCM ($R^2 \geq 0.4$) which may be related to the lower occurrence of these THM species in the sample dataset (Table 1). Emerging DBPs (DCAN, TCP and TCNM) were frequently occurring in the dataset (≥88 %) (Table 1) but showed generally poor validation performance (e.g., $R^2 \leq 0.3$). Models were most sensitive to two widely reported humic-like fluorophores (Figure 1) together with DOC or A_{254} (Figure 3). ML models derived from DOM spectroscopic variables alone, showed only marginally lower performance (<15% reduction in R^2) than models containing both hydrochemical and spectroscopic measurements.

The research also examined spatial variability in DBP formation potential across different sub-catchments, using a nested sub-basin approach to group sampling locations according to landcover characteristics. The main landcover categories considered included grassland on mineral soils, grassland on peat soils, and areas dominated by conifer plantations. Groundwater samples were considered as a separate hydrological domain. The analysis revealed significant differences in DBP formation potential across landcover types. Sub-basins with extensive conifer on peat soils exhibited the highest DBP formation potential, particularly for THMs and HAAs. This is attributed to the high concentrations of humic substances derived from organic-rich peat soils, which are highly reactive during chlorination. In contrast, grassland catchments showed moderate DBP formation potential, reflecting lower concentrations of humic substances. Groundwater sources generally exhibited lower levels of regulated DBPs, making them a potentially attractive alternative for drinking water supply. However, groundwater was also identified as a potential source of nitrogen-containing DBPs, which may be more cytotoxic and mutagenic. Further analysis of DOM composition using molecular fractionation techniques confirmed that hydrophobic organic matter plays a key role in DBP formation. These findings emphasise the importance of catchment management and land use planning in reducing DBP risks and improving water quality. The results also highlight the need for targeted interventions in high-risk catchments, such as improved land management practices and enhanced treatment processes, to mitigate the impact of DOM on DBP formation.

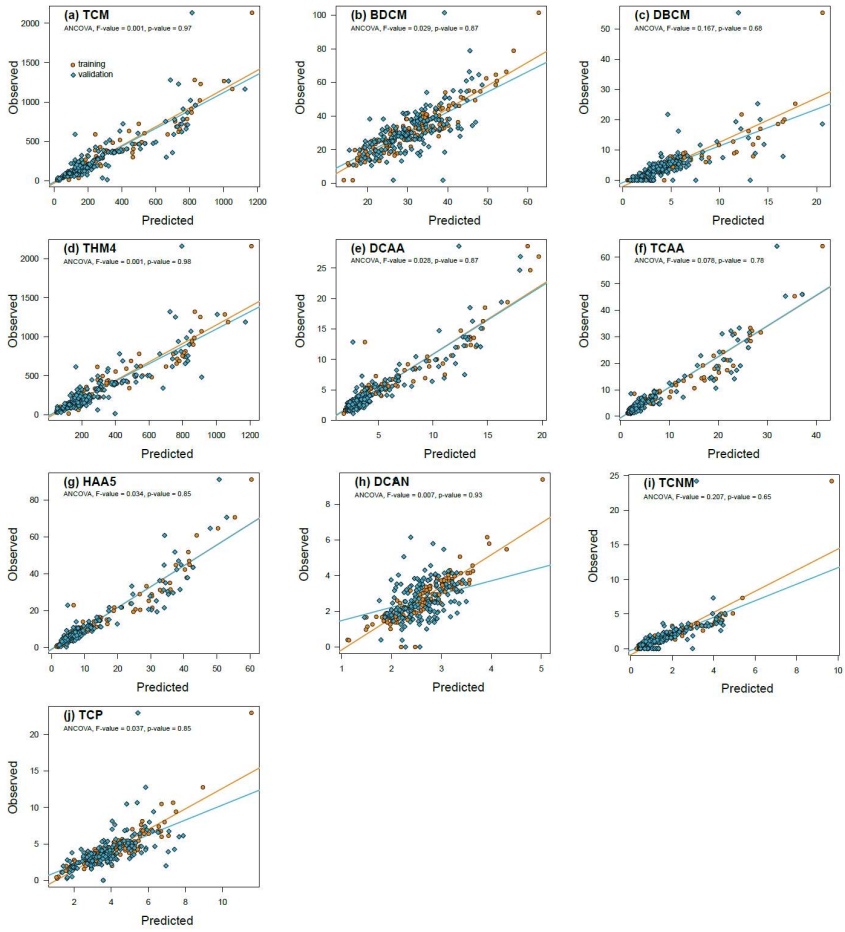

Figure 2: *Observed versus predicted DBP formation potential concentrations (µg L^{-1}) for the optimal variables model. One-way analysis of covariance (ANCOVA) shows no significant difference between training and validation results (p = >0.05) (from Droz et al., 2025).*

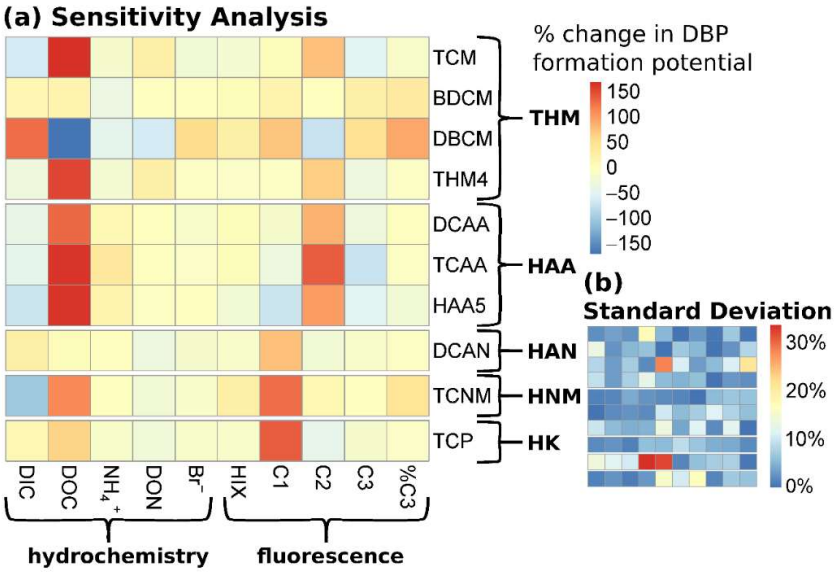

Figure 3: *Sensitivity analysis illustrating how each predictive variable influences prediction of DBP parameter concentrations (from Droz et al., 2025).*

CONCLUSIONS

The present research has demonstrated a proof-of-concept for the application of ML in the quantitative prediction of regulated and emerging DBPs in treated drinking water. Batch chlorination experiments were carried out under a Cl_2/DOC stochiometric excess with uniform conditions for all samples at pH 7 and 25 ºC for 72 hrs. ML models included NNET, BAG and a GBM with binary presence-absence classification using an SVM. Ten DBP parameter concentrations, namely THM4, HAA5, TCM, BDCM, DBCM, DCAA, TCAA, DCAN, TCNM (chloropicrin) and TCP could be quantitatively predicted (average R^2 = 0.86, root mean squared percent error = 27.9 %) with a further five species classified for binary presence-absence only (95.6 % average accuracy). Models were most sensitive to two widely reported humic-like fluorophores together with DOC or A_{254}. Inclusion of hydrochemical parameters only marginally improved model performance. The research highlights the strong influence of landcover on DBP formation, with forested peatland catchments identified as high-risk. Groundwater sources offer potential advantages in terms of lower levels of regulated DBPs but may introduce other risks associated with elevated nitrogen-containing emerging DBPs. The adoption of fluorescence-based monitoring technologies is recommended, as these systems enable rapid, non-destructive, and cost-effective assessment of raw water DOM quality. When integrated with ML models, they can provide real-time predictions of DBP formation, supporting improved process control and regulatory compliance in Ireland and around the world.

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OCCURRENCE AND DRIVERS OF ANTIMICROBIAL RESISTANCE IN GROUNDWATER: A NATIONAL STUDY OF PRIVATE WELLS IN IRELAND

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ABSTRACT

The role of the natural environment in the dissemination of antimicrobial resistant bacteria is increasingly recognised; however, knowledge of the mechanisms governing their occurrence remains limited, particularly in relatively 'pristine' groundwater environments. Ireland is characterised by high groundwater reliance, with private (unregulated) wells supplying drinking water to over 15% of the population. These supplies are typically located in rural areas where risks of microbiological contamination are elevated due to intensive agricultural practices and widespread use of domestic wastewater treatment systems, both of which may act as sources of antimicrobials and resistant bacteria. This study aimed to quantify antimicrobial resistance (AMR) in private wells across Ireland and identify associated environmental and infrastructural risk factors. A total of 250 groundwater samples from 132 wells were analysed for Escherichia coli and Pseudomonas aeruginosa. Isolates from contaminated samples were tested for susceptibility to 18 and 9 antimicrobials, respectively. Results showed that 16.3% of E. coli isolates were resistant to at least one antimicrobial, with a further 79.6% classified as intermediately resistant. In contrast, no categorical resistance was detected among P. aeruginosa, with only one isolate showing intermediate resistance. Multivariate analysis indicated significantly higher odds of resistant E. coli detection with increasing cattle density (OR = 1.028, p = 0.032), while no significant associations were observed with human-derived contamination sources. Resistance was highest to veterinary antimicrobials, including streptomycin (14.3%), tetracycline (12.2%), and ampicillin (12.2%). Model outputs also suggest overland flow and direct wellhead ingress as key transport pathways. These findings highlight the importance of agricultural pressures in AMR dissemination and may inform groundwater protection and surveillance strategies.

Key words: *Antimicrobial Resistance, Groundwater, Drinking Water, Agriculture*

INTRODUCTION

The global public health burden of antimicrobial resistance (AMR) and its rapid dissemination has been widely recognised in recent decades (Bradford and Harvey, 2017; Larsson et al., 2018; Opatowski et al., 2019). Increasing evidence demonstrates the presence of resistant bacteria and resistance genes in non-clinical environments, including aquatic systems (Hooban et al., 2021; Hooban et al., 2022), soils (Zhao et al., 2019), food crops (Cerqueira et al., 2019), and vegetation (Obermeier et al., 2021). This widespread environmental distribution is associated with increasing rates of severe and difficult-to-treat infections (Opatowski et al., 2019; CDC, 2019), with over 35,000 and 33,000 deaths annually reported in the United States and Europe, respectively (CDC, 2019). The rise of AMR is largely driven by the misuse and overuse of antimicrobials, coupled with limited development of new drugs (Miethke et al., 2021). The World Health Organization (WHO) reports that only two of eleven antibiotics approved since 2017 represent novel classes (WHO, 2021), while antimicrobial use has increased globally, including during the COVID-19 pandemic (Yates et al., 2020; Langford et al., 2020; Rawson et al., 2020). Groundwater has recently been identified as an important reservoir for antimicrobial resistant bacteria (Andrade et al., 2020), despite earlier evidence of its occurrence (Cooke et al., 1976). Although often considered a relatively pristine resource, groundwater can act as both a source and pathway for AMR transmission (Sanderson et al., 2018), as well as a direct exposure route for humans (Coleman et al., 2012). This is particularly significant given that over 2.2 billion people rely on groundwater for drinking water with

additional indirect exposure through agricultural irrigation (Verraes et al., 2013). Small-scale groundwater supplies are frequently unregulated and lack adequate treatment, increasing susceptibility to contamination (Hynds et al., 2014; Murphy et al., 2017). Groundwater systems can also support microbial persistence and the co-selection of resistance due to the presence of pollutants such as trace metals and biocides. Given the already substantial burden of groundwater-associated infection, estimated at over 35.2 million gastrointestinal cases annually (Murphy et al., 2017), the presence of antimicrobial resistant bacteria represents a significant public health concern. Despite this, limited understanding exists regarding the environmental and anthropogenic factors influencing AMR occurrence in groundwater systems. This study therefore employed hydrogeological fieldwork, microbiological analysis, and statistical modelling to assess (i) the prevalence of antimicrobial resistance in groundwater bacteria, (ii) key environmental and infrastructural factors associated with resistance, and (iii) potential sources and transport pathways. Two indicator organisms were selected: Escherichia coli, a faecal indicator commonly used in groundwater AMR studies (Andrade et al., 2020), and Pseudomonas aeruginosa, an environmental bacterium associated with human activity and infrastructure. The *Pseudomonas* genus has also been identified as exhibiting high resistance rates in groundwater systems globally (Andrade et al., 2020). The Republic of Ireland (RoI) provides an appropriate case study due to its diverse hydrogeology, intensive agricultural activity, and high reliance on private groundwater supplies in rural areas (CSO, 2016a; CSO, 2016b). The findings provide a baseline assessment of antimicrobial resistance in groundwater and support the development of targeted source protection strategies and AMR policy initiatives.

METHOD

STUDY AREA

The study was conducted in rural areas across the Republic of Ireland (RoI), where groundwater is widely used for domestic and agricultural purposes. In 2019, over 180,000 groundwater wells were in operation, with private (unregulated) wells supplying drinking water to approximately 11% of the population. These supplies are typically located in areas of intensive agriculture and dispersed housing, increasing vulnerability to contamination. The RoI is characterised by diverse hydrogeology, with predominantly sedimentary bedrock (limestone, sandstone, shale). Most aquifers are unconfined, with vulnerability ranging from low to extreme depending on subsoil characteristics/ Karst and fractured bedrock systems facilitate rapid contaminant transport with limited attenuation, while low-permeability clay subsoils provide greater protection.

SAMPLE COLLECTION AND ANALYSIS

Private household wells were recruited nationwide through public outreach. Sampling was exploratory and not restricted by hydrogeological or infrastructural characteristics. Samples were collected from outdoor taps prior to treatment to represent raw groundwater quality. Sampling was conducted during two periods: September–November 2019 and June–August 2021. Water was collected in sterile 100 mL vessels following flushing (≥2 L for ≥60 seconds). Samples were transported at 4 °C and analysed within six hours. *Escherichia coli* and *Pseudomonas aeruginosa* were quantified using ISO-approved IDEXX Colilert and Pseudalert methods. Samples were incubated at 37 °C for 24 hours, and bacterial concentrations were determined using most probable number (MPN) methods. From each positive sample, a single isolate was cultured on MacConkey agar and incubated at 37 °C for 24 hours. Presumptive colonies were confirmed using standard reference strains. Where necessary, additional wells were tested to obtain viable isolates. Antimicrobial susceptibility was assessed using the Kirby–Bauer disc diffusion method following CLSI guidelines. Isolates were standardised to 0.5 McFarland and cultured on Müller-Hinton agar prior to application of antimicrobial discs. Plates were incubated at 37 °C for 16–18 hours. Zones of inhibition were measured and interpreted using CLSI breakpoints, with isolates classified as Resistant (R), Intermediate (I),

or Susceptible (S). A total of 18 antimicrobials were tested for *E. coli* and 9 for P. aeruginosa. Quality control was ensured using reference strains.

ENVIRONMENTAL AND INFRASTRUCTURAL RISK FACTORS

Potential risk factors were assessed using field observations and spatial datasets and grouped into environmental, household, and infrastructural categories. Hydrogeological variables (e.g., groundwater vulnerability, aquifer type) were obtained from Geological Survey Ireland datasets, while livestock density and wastewater system data were derived from Central Statistics Office records and refined using CORINE land-use data. Rainfall variables (5-, 10-, 30-, and 60-day cumulative totals) were obtained from Met Éireann. Site surveys within 100 m of each well recorded proximity to livestock and wastewater systems, structural integrity, and well characteristics. Household antimicrobial usage was collected via questionnaire. Associations between risk factors and microbial outcomes were initially assessed using Chi-square tests (categorical variables) and Mann–Whitney U tests (continuous variables). Multivariate binary logistic regression was then used to identify predictors of bacterial presence and antimicrobial resistance. Highly correlated variables were assessed separately, with model selection based on Nagelkerke R^2. Variables with substantial missing data (>10%) were excluded, and all remaining variables were entered using a forced-entry approach. Analyses were conducted using IBM SPSS (version 28).

RESULTS

A total of 132 private wells were sampled across 21 counties in the Republic of Ireland, yielding 250 groundwater samples across two sampling rounds (2019 and 2021). Most wells were drilled (88.6%; n = 117), with a mean depth of 40.9 ± 27.7 m. Protective infrastructure was variable: only 34.8% of wells had sealed caps and 24.2% had protective casing, while 60.6% had casing clearance below the recommended 150 mm threshold. Wells were predominantly located in areas of high (36.4%) and extreme (27.3%) groundwater vulnerability, with most situated in poorly productive bedrock aquifers (81.8%). Smaller proportions were located in karst (12.9%), fractured bedrock (3.0%), and gravel aquifers (2.3%) (Table 1). Potential contamination sources were common: 14.4% of wells were within 30 m of a domestic wastewater treatment system (DWWTS), and 18.9% were within 3 m of livestock. Mean livestock densities were 161 ± 59 cattle and 95 ± 137 sheep per km², with an average DWWTS density of 8 ± 5 units/km². The majority of households (84.8%) used well water for drinking, with an average consumption of 1,320 ± 613 ml per person per day. Antimicrobial use was reported in 17.2% and 30.8% of households in the three and six months prior to sampling, respectively. Microbial contamination was observed across the study area, with both *Escherichia coli* and *Pseudomonas aeruginosa* detected in groundwater samples. Overall, *E. coli* was present in 21.6% of samples, with higher detection rates in Round 1 (26.5%) compared to Round 2 (16.1%). At the well level, *E. coli* was detected at least once in 33.3% of wells (n = 44). In contrast, *P. aeruginosa* occurrence was lower, detected in 4.8% of samples and 8.3% of wells (n = 11). Recurrent contamination (i.e., detection at the same site across sampling rounds) was more common for *E. coli* (9.1%; n = 12 wells) than for *P. aeruginosa* (0.7%; n = 1 well). The spatial distribution of contamination is illustrated in Figure 1, which shows widespread occurrence across 17 of the 21 sampled counties. Hydrogeological patterns differed between species. Notably, *P. aeruginosa* was not detected in areas classified as having low groundwater vulnerability, while the highest detection rates occurred in extreme vulnerability settings (17.2%; n = 5 samples). In contrast, *E. coli* contamination was relatively consistent across vulnerability classes, with detection rates ranging from 21.2% to 26.3%, suggesting broader environmental controls on its occurrence.

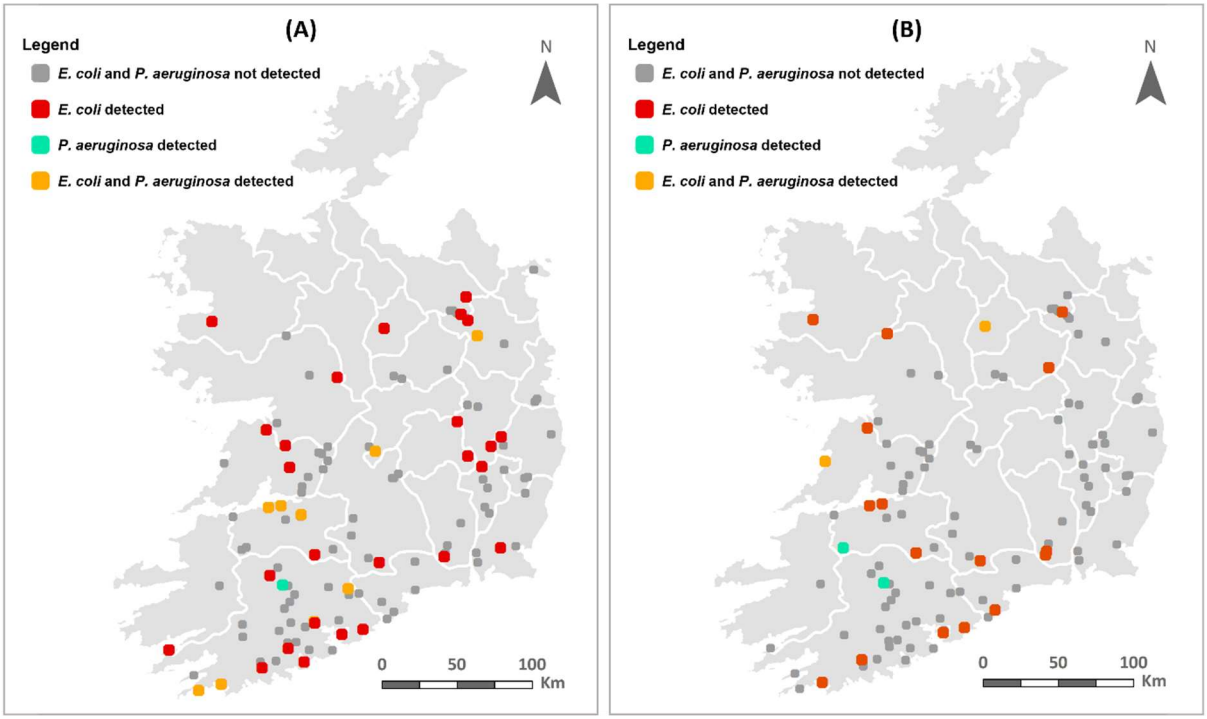

Figure *1*: Republic of Ireland maps showing the geographical distribution of sampled wells and contamination status in (A) Round 1 samples (collected in autumn 2019), and (B) Round 2 samples (collected in summer 2021)

ANTIMICROBIAL RESISTANCE PROFILES

Phenotypic antimicrobial susceptibility testing was conducted on 49 *E. coli* and 6 *P. aeruginosa* isolates. A small number of *E. coli* isolates from Round 1 could not be recovered and were excluded. Overall, 16.3% (n = 8) of *E. coli* isolates were resistant to at least one antimicrobial, with multidrug resistance observed in 12.2% (n = 6). A high proportion (95.9%; n = 47) were classified as "not susceptible." In contrast, no categorical resistance was detected in *P. aeruginosa*, although one isolate showed intermediate resistance to enrofloxacin. Across all samples, resistant *E. coli* were detected in 3.2% of samples and 6.1% of wells, with no repeated detection across sampling rounds. Resistance in *E. coli* was most frequent for streptomycin (14.3%), with widespread intermediate resistance (81.6%). Tetracycline and ampicillin showed similar resistance rates (15.8%), followed by piperacillin (10.2%). Lower resistance levels were observed for chloramphenicol (4.1%), trimethoprim (2.0%), and trimethoprim-sulfamethoxazole (2.0%). Although no resistance to cefazolin was identified, over half of isolates (53.1%) exhibited intermediate susceptibility. All isolates remained fully susceptible to key antimicrobials including imipenem, piperacillin-tazobactam, ceftazidime, gentamicin, and aztreonam, indicating preserved efficacy of several clinically important agents despite widespread reduced susceptibility.

MULTIVARIATE LOGISTIC REGRESSION MODELLING

Multivariate logistic regression was used to assess predictors of (i) *P. aeruginosa* presence, (ii) *E. coli* presence, and (iii) resistant *E. coli* occurrence (Table 1). Model performance was moderate (Nagelkerke R^2 = 0.504, 0.285, and 0.475, respectively). For *P. aeruginosa*, no significant hydrogeological or agricultural associations were identified, although lower sheep density showed a marginal relationship (OR = 0.959, p = 0.056).

Table 1: Final multivariate binary logistic regression models for presence/absence of (i) Pseudomonas aeruginosa, (ii) Escherichia coli, and (ii) Resistant Escherichia coli

Risk Factors	*P. aeruginosa* detection (n=233)		*E.coli* detection (n=233)		Resistant [a] *E.coli* detection (n=228)	
	OR (95% CI)	*p*-value	OR (95% CI)	*p*-value	OR (95% CI)	*p*-value
Groundwater vulnerability						
Low	0.000 (0.000 – .)	0.997	Reference		Reference	
Moderate	0.187 (0.010 – 3.460)	0.260	0.446 (0.094 – 2.109)	0.308	0.000 (0.000 – .)	0.997
High	0.320 (0.028 – 3.657)	0.359	0.569 (0.164 – 1.972)	0.374	**0.003 (0.000 – 0.423)**	**0.022***
Extreme	0.134 (0.010 – 1.893)	0.137	1.247 (0.349 – 4.461)	0.734	**0.039 (0.002 – 0.990)**	**0.049***
Extreme-karst	Reference		0.946 (0.225 – 3.972)	0.940	**0.027 (0.001 – 0.858)**	**0.041***
Aquifer type						
Karst vs Non-karst (Ref)	6.309 (0.628 – 63.364)	0.118	**3.903 (1.413 – 10.782)**	**0.009***	0.397 (0.017 – 9.368)	0.567
Sheep density [b]						
Increases of 1 head/m^2	0.959 (0.918 – 1.001)	0.056**	1.001 (0.998 – 1.004)	0.519	0.991 (0.977 – 1.005)	0.196
Cattle density [b]						
Increases of 1 head/m^2	1.000 (0.983 – 1.017)	0.983	**1.010 (1.002 – 1.018)**	**0.011***	**1.028 (1.002 – 1.056)**	**0.037***
DWWTS density [b]						
Increases of 1 unit/m^2	0.994 (0.884 – 1.118)	0.920	1.025 (0.961 – 1.094)	0.455	0.973 (0.709 – 1.335)	0.833
Nearest livestock ≤3 m						
Present vs. Absent (Ref)	0.067 (0.002 – 1.979)	0.118	1.071 (.412 – 2.785)	0.888	4.977 (0.632 – 39.193)	0.127
Nearest DWWTS ≤30 m						
Present vs. Absent (Ref)	**14.046 (1.380 – 142.963)**	**0.026***	**5.090 (1.934 – 13.401)**	**<0.001***	0.000 (0.000 – .)	0.998
5-day rainfall						
Increases of 1 mm	**1.069 (1.020 – 1.121)**	**0.005***	-	-	-	-
60-day rainfall						
Increases of 1 mm	-	-	**1.008 (1.002 – 1.014)**	**0.008***	1.009 (0.993 – 1.025)	0.287
Supply type						
Hand-dug vs. Drilled (Ref)	**18.902 (1.587 – 225.127)**	**0.020***	**7.199 (2.252 – 23.016)**	**<0.001***	**41.071 (1.001 – 1685.502)**	**0.050***
Sealed cap						
Present vs. Absent (Ref)	0.358 (0.037 – 3.422)	0.372	0.452 (0.193 – 1.060)	0.068**	0.155 (0.017 – 1.410)	0.098**
Wellhead cracks						
Present vs. Absent (Ref)	**100.256 (3.114 – 3227.933)**	**0.009***	2.847 (0.752 – 10.782)	0.124	0.000 (0.000 – .)	0.998
Casing clearance ≥150 mm						
Present vs. Absent (Ref)	0.731 (0.118 – 4.519)	0.736	0.603 (0.273 – 1.331)	0.211	1.323 (0.104 – 16.872)	0.829
Nagelkerke R^2	0.504		0.285		0.475	

[a] Categorically resistant in accordance with CLSI (2018; 2020); [b] Sheep, cattle and DWWTS densities calculated per Small Area, which are delineated land sections in the RoI territory which comprise 80 to 120 dwellings (CSO, 2016b); DWWTS = Domestic Wastewater treatment System; CI = Confidence Interval; * p-value ≤ 0.05; ** 0.05< p-value ≤ 0.1

Detection was strongly associated with proximity to DWWTS (<30 m) (OR = 14.046, p = 0.026) and short-term rainfall (5-day) (OR = 1.069 per mm, p = 0.005). Infrastructure was also important, with higher odds observed in hand-dug wells (OR = 18.902, p = 0.020) and wells with structural defects such as cracks (OR = 100.256, p = 0.009). Similar trends were observed in alternative models, with 10-day rainfall also significant. For *E. coli*, hydrogeological and environmental controls were more evident. Contamination was more likely in karst aquifers (OR = 3.903, p = 0.009) and increased with cumulative rainfall over 60 days (OR = 1.008 per mm, p = 0.008). Anthropogenic factors were also significant, with higher odds associated with proximity to DWWTS (OR = 5.090, p < 0.001) and increasing cattle density (OR = 1.010, p = 0.011). Hand-dug wells again showed elevated risk (OR = 7.199, p < 0.001), while absence

of a sealed cap showed a marginal association (OR = 2.212, p = 0.068). For resistant *E. coli*, distinct patterns were observed, with significantly higher detection in areas of low groundwater vulnerability compared to higher vulnerability settings, suggesting different transport or persistence mechanisms.

DISCUSSION

The present study represents the second investigation of antimicrobial resistant bacteria in groundwater in the Republic of Ireland (RoI), and the first to employ a nationwide sampling network incorporating bacteria from distinct ecological niches. A total of 132 private wells (250 samples) across 21 counties were analysed over two sampling periods, providing a robust dataset to assess antimicrobial resistance (AMR) occurrence, sources, and pathways. *P. aeruginosa* contamination was relatively low (8.3% of wells), while *E. coli* was detected in 33.3% of wells, consistent with previous Irish studies (Hynds et al., 2012; O'Dwyer et al., 2018). The low prevalence of *P. aeruginosa* aligns with findings from rural environments (Bamigboye et al., 2020; Ayad et al., 2021) and likely reflects reduced anthropogenic pressure compared to urban systems (Chatterjee et al., 2017; Crone et al., 2019). Marked differences in antimicrobial resistance were observed between species. Resistance occurred in 16.3% of *E. coli* isolates, with 75% exhibiting multidrug resistance, whereas no categorical resistance was detected in P. aeruginosa. This contrasts with global reports of resistant Pseudomonas spp. in groundwater (Andrade et al., 2020), but likely reflects lower selective pressures in rural environments. Intrinsic resistance mechanisms in *P. aeruginosa* (Livermore, 1984; Nordmann and Guibert, 1998), combined with limited susceptibility breakpoints for veterinary antimicrobials, also complicate interpretation. Resistance in *E. coli* was relatively high compared to international studies (Coleman et al., 2013; Andrade et al., 2020), though lower than previous Irish findings (O'Dwyer et al., 2017), potentially reflecting differences in classification thresholds (Kozak et al., 2009; Allen et al., 2011). Resistance in *E. coli* was most frequently associated with veterinary antimicrobials such as streptomycin, tetracycline, and ampicillin (O'Dwyer et al., 2017; Martin et al., 2020), consistent with their widespread use in Irish cattle farming (Gibbons et al., 2014) and resistance patterns observed in bovine-associated isolates (Karczmarczyk et al., 2011). In contrast, resistance to antimicrobials used exclusively in human medicine was low, suggesting limited human-derived influence. Co-resistance between piperacillin and ampicillin likely reflects shared β-lactamase mechanisms (Brown et al., 2010; Hussain et al., 2021). Multivariate modelling identified agricultural activity as the dominant driver of AMR. While *E. coli* presence was associated with both proximity to domestic wastewater treatment systems (DWWTS) and cattle density, only cattle density was linked to resistant *E. coli*, indicating a stronger influence of zoonotic sources. This is consistent with previous studies (O'Dwyer et al., 2017; Coleman et al., 2013; Gambero et al., 2017) and reflects the importance of cattle farming in Ireland (CSO, 2021). Seasonal increases in resistance may be associated with antimicrobial use during calving (Gibbons et al., 2014). Human-derived pressures appeared less significant, as *P. aeruginosa* detection was linked to DWWTS proximity but not to resistance patterns, consistent with findings that AMR in groundwater increases near densely populated areas (Moore et al., 2020). Analysis of transport pathways suggests that *E. coli* contamination occurs via multiple mechanisms, including rapid recharge in karst systems, rainfall-driven infiltration, and direct wellhead ingress. In contrast, resistant *E. coli* was associated with poorly sealed wells and low-vulnerability settings, indicating overland flow followed by direct ingress as the primary pathway. Similar patterns were observed for P. aeruginosa, where detection was linked to short-term rainfall and well defects, suggesting localised contamination. Hand-dug wells were consistently associated with increased contamination risk, supporting previous findings (Hynds et al., 2012; Maran et al., 2016). The absence of repeated detection across sampling rounds indicates that AMR contamination is dynamic and episodic, influenced by short-term environmental conditions. Overall, findings highlight the dominant role of agricultural pressures, the importance of well construction and maintenance, and the differing behaviour of faecal and environmental bacteria. Protective measures include improved well design, adequate setback distances, and structural maintenance. Although resistance prevalence was

relatively low, its presence in drinking water remains a public health concern. Groundwater is a recognised transmission pathway for gastrointestinal illness (Murphy et al., 2020), and private well use in Ireland has been linked to increased infection risk (ÓhAiseadha et al., 2017). Even low-level AMR contamination may therefore contribute to increased morbidity and treatment challenges. Continued monitoring and targeted mitigation strategies are required to limit AMR dissemination and protect public health.

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SESSION VI

GEMINI AND GROUNDWATER INTERACTIONS OF GEOTHERMAL ENERGY DEVELOPMENT

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ABSTRACT

GEMINI is a €20 million cross-border geothermal energy demonstration project, undertaking a series of activities to de-risk shallow and deep geothermal development across the island of Ireland.

Delivered by an interdisciplinary partnership spanning multiple sectors, GEMINI's four demonstration sites will each feature a different geothermal technology or study, providing key information on geothermal prospectivity across multiple geological settings.
Works include the delivery of operational shallow open and closed-loop geothermal systems, deep drilling in an urban setting, and geophysics data acquisition and modelling to characterise key geological settings, such as fractured carbonates in Dublin and sandstone reservoirs in Antrim and Belfast.
Geothermal systems, whether they are closed-loop, open-loop, or thermal energy storage technologies, each have distinct considerations for groundwater interactions.
GEMINI will provide new data and insights into fluid-flow characterisation, the thermal properties of different aquifers, and the overall geothermal potential of reservoirs in Ireland.
These data will be used to provide guidance on technical solutions, cost insights, legislation, and planning systems, informing stakeholders and regulators to support the long-term growth of a sustainable geothermal sector in Ireland.

Key words: *geothermal, energy, shallow, deep, open-loop, closed-loop, aquifer*

INTRODUCTION

Geothermal energy is defined as energy stored in the form of heat beneath the surface of solid earth, and it can be accessed to provide a variety of applications, including heating, cooling and, in some settings, electricity generation.

As a low-carbon, locally available renewable energy source, geothermal energy use offers a variety of benefits; however, despite its availability and accessibility, geothermal is currently underutilised across the island of Ireland, lagging behind neighbouring countries in developing its geothermal resources.

Climate legislation committing to greenhouse gas emission reductions, as well as several geopolitical events and shocks to global energy markets, have led to growing awareness and interest in geothermal energy in recent years.

To respond to these challenges and increase the uptake of geothermal energy on the island of Ireland, GEMINI will de-risk projects and accelerate geothermal market development through practical demonstration and investment.

GEMINI has three key objectives: (i) de-risk shallow and deep geothermal energy projects, (ii) develop and support a market, skilled jobs, policy, and regulation for geothermal energy, and (iii) create the conditions for meaningful engagement and public participation in developing a clean, sustainable energy solution on the island of Ireland.

The project is supported by the PEACEPLUS Programme, managed by the Special EU Programmes Body (SEUPB) and endorsed by the Department of the Environment, Climate and Communications (Ireland) and the Department for the Economy (Northern Ireland).

This paper provides an overview of GEMINI, geothermal resources and the different types of systems that use it, as well as interactions with the groundwater environment in geothermal energy development.

GEOTHERMAL OVERVIEW

Geothermal energy is derived from multiple sources, terrestrial and non-terrestrial, depending on the setting. The surface of the Earth acts as a thermal collector, absorbing incoming solar energy that controls temperatures in the shallow subsurface. Seasonal temperature fluctuations control temperatures in the initial 10 metres of the subsurface, beneath which temperature varies with climatic conditions and is influenced by atmospheric effects (Banks, 2012).

The majority of the thermal energy stored within the Earth is derived from internal processes, including primordial heat generated during the formation of the planet, and the continual radiogenic decay of elements within the Earth's interior. This heat slowly migrates towards the cooler surface of the Earth via heat transport processes.

The rate at which temperature increases with depth is known as the geothermal gradient, which represents the outward flow of heat from the Earth's interior. The geothermal gradient varies globally, with numerous factors, including geological setting and structural context, influencing the distribution of temperatures. Subsurface temperature modelling of Ireland illustrates the local variability of geothermal gradients.

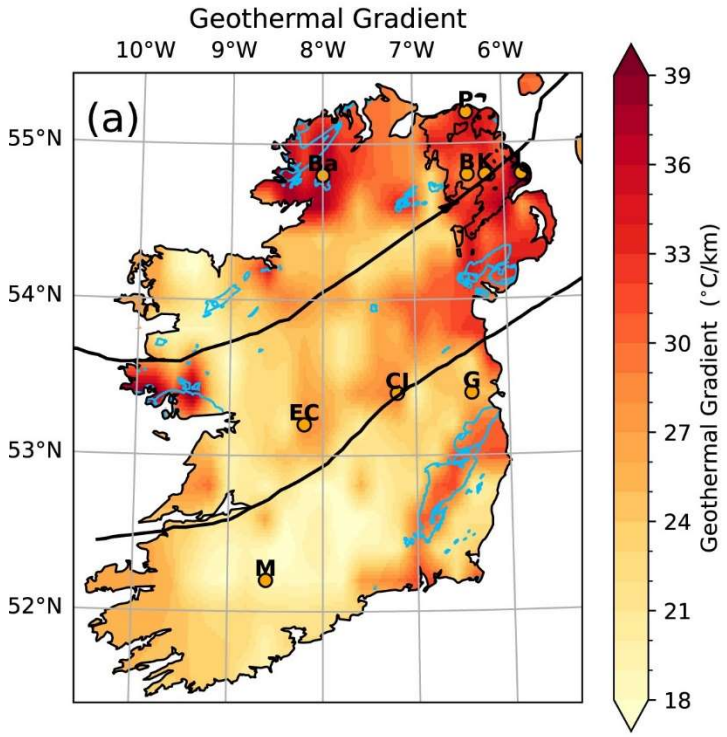

Figure 1: *Geothermal gradient map of Ireland (Chambers et al., 2025)*

Results indicate that across the island, geothermal gradients range from <20°C/km^{-1} in the south and Midlands, up to ~40°C/km^{-1} beneath granitic regions in Donegal and Galway (Chambers et al., 2025). Much of Northern Ireland is underlain by elevated geothermal gradients due to the presence of the Antrim Lava Group. These basalts have a relatively low thermal conductivity, insulating heat within the more thermally conductive sandstone reservoirs underlying the group.

GEOTHERMAL TECHNOLOGIES

Geothermal energy is a highly versatile resource that can be extracted in multiple ways according to the geological setting and target depth. Geothermal systems can be broadly classified as either shallow or deep, and while there is no strict definition between the two, in geothermal, 'shallow' typically refers to depths up to 500 metres, and 'deep' is greater than 500 metres.

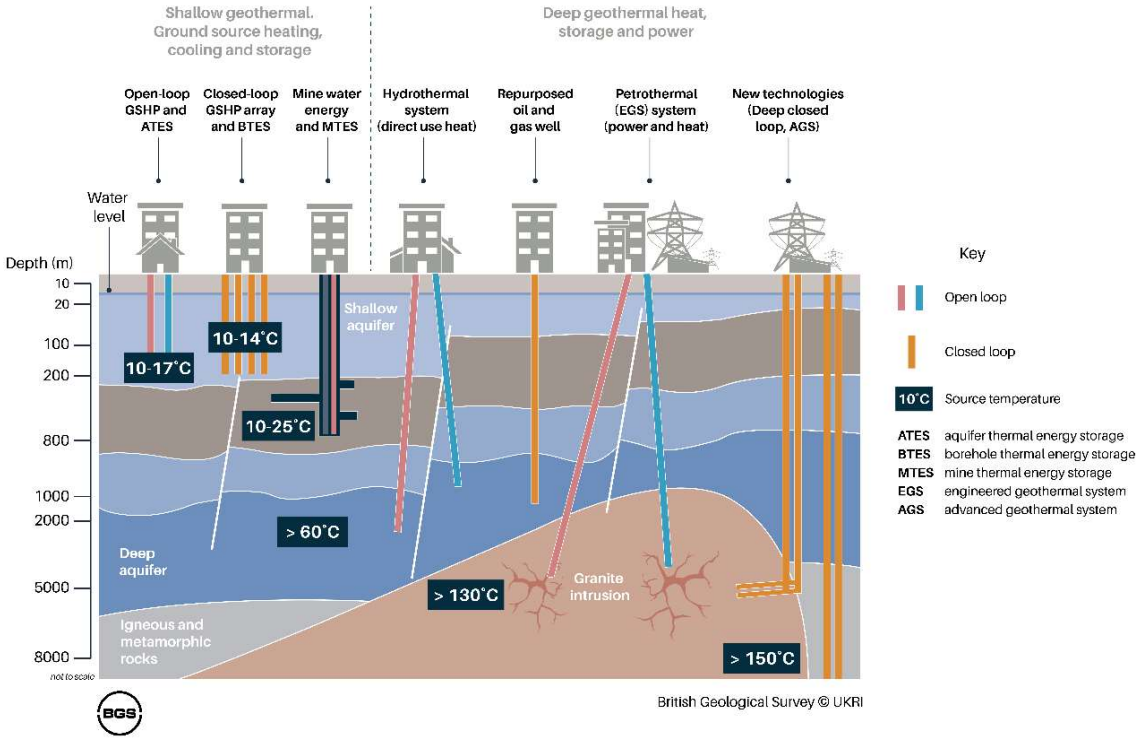

Figure 2: *Schematic image of geothermal technologies (heat, cool and underground thermal storage) BGS©UKRI*

SHALLOW GEOTHERMAL ENERGY

Shallow geothermal resources at temperatures between 10 and 25° are available almost everywhere in Ireland and require the use of ground-source heat pumps to raise temperatures to suitable levels for space heating in buildings.

CLOSED-LOOP GROUND-SOURCE HEAT PUMP SYSTEMS

Closed-loop systems collect heat by circulating a heat-carrier fluid through different configurations of buried pipework and borehole heat exchangers.

The heat output is scaled to meet the user's demand by adjusting the length of the heat-exchange interface, such as by drilling multiple boreholes or varying the depth that each borehole is drilled to.

OPEN-LOOP GROUND-SOURCE HEAT PUMP SYSTEMS

Open-loop systems use groundwater pumped directly from aquifers for heat exchange, discharging the thermally spent water once complete. Typically, a minimum of two wells are drilled to operate an open-loop system: one for abstraction and another for reinjection back into the subsurface. Due to the reliance of suitably productive aquifers to abstract groundwater from, open-loop systems are constrained to certain geographical areas, whereas closed-loop systems may be suitable in practically all locations. However, where feasible, open-loop systems can offer improved system efficiencies and lower capital costs for installation.

DEEP GEOTHERMAL ENERGY

Deep geothermal resources are accessed by drilling deep wells to attain temperatures sufficient for direct-use heating or, in some settings, power generation.

HYDROTHERMAL SYSTEMS

Hydrothermal systems use aquifers of sufficient quality to transmit and store water or brine. Where such aquifers are buried in deep sedimentary basins, they form hot sedimentary aquifers or hydrothermal systems. Hot sedimentary aquifers suitable for deep geothermal energy are present across the island; in Northern Ireland, the Permo-Triassic sandstones extend from shallow ranges beneath Belfast to their greatest depths beneath Antrim (Raine & Reay, 2019), and in Ireland, Carboniferous limestones occur in multiple places, including at suitable depths beneath Dublin.

PETROTHERMAL SYSTEMS

Petrothermal systems occur where there is hot rock but insufficient natural fluid or permeability to transport heat to the surface. Granites, though relatively impermeable, can store and transmit fluids where they are naturally faulted or fractured. As they can contain a relatively high proportion of radioactive elements, they are targets for geothermal energy exploitation, where heat from the decay of these elements accumulates. These systems are usually developed for power generation, although they can contain a heating component. The basic design consists of a well doublet drilled into the fractured system to create a production and re-injection circuit.

GROUNDWATER CONSIDERATIONS

Geothermal energy is inherently linked with the groundwater environment, and developers must consider these interactions when installing geothermal systems, regardless of technology type. These include how groundwater may be used in system design, either as a heat source or to optimise heat recovery, and how an operating system may impact the local environment.

While the increased attention on geothermal has spurred the development of bespoke legislation to govern its extraction, most geothermal energy use is governed by environmental regulatory frameworks, which may not be appropriate in all instances. For example, the EU's Water Framework Directive (WFD, 2000/60/EC) includes heat within its definition of pollution, despite it not being a substance.

Open-loop systems are often subject to increased regulatory scrutiny, as they involve the abstraction and discharge of groundwater from aquifers. Factors typically considered in an open-loop system application include changes in water quality, potential aquifer depletion, and the risk of local environmental damage from drilling activities.

As the operation of closed-loop systems doesn't require abstraction or discharge of groundwater, regulatory requirements for their installation may be less than those of open-loop systems. Proposals will typically be acceptable if the installation won't threaten groundwater resources, such as by drilling on a heavily contaminated site or using drilling fluids that could pose a risk to drinking water.

Less constrained by current regulations are thermal risks to local ecosystems or microbiology resulting from system operation. In most cases, environmental risks can be mitigated through responsible installation design and techniques. The greatest risk from the thermal effects of geothermal systems arises when large-scale, unbalanced demand is sustained for extended periods of time.

Instances of large open-loop cooling schemes, where groundwater is used to reject heat into the subsurface, can cause a 'thermal plume' of warm groundwater within a relatively cooler aquifer, which travels down the hydraulic gradient. If this thermal plume were to reach a surface discharge point and significantly elevate surface water temperatures, nearby

ecological receptors could be affected. Such a scenario is unlikely to occur due to the volumetric heat capacities of surrounding rock units, which reduce the speed and distance that a potential thermal plume is able to migrate (Todd and Banks, 2009).

GEMINI

The GEMINI Project is working to build momentum towards the use of this already established, mature technology on the island of Ireland, harnessing cross-border collaboration between public bodies, academia and communities.

Central to the project is the development of installation demonstration sites, creating opportunities to showcase geothermal energy capability across the island. Throughout the four-year project, GEMINI is collecting data to further increase knowledge of the island's subsurface and potential geothermal resources, which will be compiled into heat resource maps and made publicly available.

In addition to the demonstration sites, two feasibility studies are being undertaken, with one in County Antrim and another in the Lough MacNeans area. In County Antrim, several geophysical surveys are being conducted to gather data that will inform 3D modelling and geothermal resource assessment of the region. In the Lough MacNeans area, a social science study will focus exclusively on community engagement through a deliberative democracy programme.

With specific policies, legislation, and regulations, as well as government support, still lacking for geothermal energy across the island, GEMINI is setting in motion national regulatory frameworks and cross-border policy advice for geothermal energy, as well as developing targeted toolkits for decision-makers.

In preparation for a future scaling up of geothermal energy capacity across the island, GEMINI is developing skills-sharing platforms and training opportunities for relevant professionals, supporting businesses in the emerging geothermal market, creating multi-level education modules and shaping models for community engagement. It will deliver long-term value through the development of data, tools, skills and policy insights, supported by geological mapping and drilling results. GEMINI's work will also aim to make it easier for potential users to calculate the costs involved.

GEMINI is supported by the PEACEPLUS programme, managed by the Special EU Programmes Body (SEUPB) and endorsed by the Department of the Environment, Climate and Communications (Ireland) and Department for the Economy (Northern Ireland).

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For further information on the GEMINI project, please visit: www.geminigeothermal.com

River Water Level Prediction in Ireland: Comparative Forecasting and Leakage-Free Meta-Learning for Station-Aware Model Selection

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ABSTRACT

Accurate river water level forecasting is central to flood preparedness, drought management and catchment-scale decision-making across Ireland. A persistent operational challenge, however, is that forecasting performance is strongly site-dependent: a model that performs well at one hydrometric station may not generalise to another. As a result, model selection should be treated as a primary methodological concern rather than a secondary implementation step. This study introduces a two-stage framework for river water level prediction and station-aware model selection. In the first stage, a suite of candidate models — including linear, dense and recurrent neural architectures — is evaluated for one-hour-ahead prediction using historical observations from Irish hydrometric stations. Recurrent models, particularly LSTM and GRU, frequently exhibit strong predictive capability, yet no single architecture is consistently optimal across the full station network. In the second stage, this station- level heterogeneity is formalised as a leakage-free meta-learning problem. A meta-dataset is constructed using temporal, spatial and hydrogeological descriptors, alongside static representations of candidate models, while explicitly excluding all post-training performance variables to prevent target leakage. Under grouped leave-one-station-out evaluation, the resulting ranking-based framework reliably identifies near-optimal models for previously unseen stations, consistently reducing the candidate space to a small set of high-quality recommendations while maintaining minimal performance regret relative to the optimal choice. These findings demonstrate that leakage-free meta-learning provides a principled and operationally viable approach to model selection in hydrological forecasting. The results further indicate that station context encodes actionable information that can be systematically exploited, supporting a shift towards context-aware, transferable forecasting workflows across heterogeneous hydrometric networks.

Key words: *machine learning; water level prediction; hydrologic time series forecasting; meta-learning; model selection; Ireland.*

INTRODUCTION

Accurate river water level forecasting supports flood preparedness, drought response and day- to-day catchment management. Physically based hydrologic and hydrodynamic models remain central to water science, but they can be difficult to calibrate and operationalise when detailed process information is limited (Kaya et al., 2019; Paiva et al., 2011). Data-driven forecasting methods are therefore attractive in hydrology because they can learn predictive structure directly from historical observations and can often be deployed more rapidly than fully process-based approaches (Bhagat et al., 2022; Shen, 2018; Kratzert et al., 2019).

Machine learning models have shown strong performance for hydrological time-series prediction, including river stage, groundwater level and related environmental variables (Müller et al., 2021; Zhang et al., 2018; Durdu, 2010). Recurrent neural architectures are particularly appealing because they can represent temporal dependence in sequential data (Cho et al., 2014; Hochreiter and Schmidhuber, 1997). A persistent practical difficulty, however, is that performance is strongly site-dependent: the forecasting model that performs best at one station may not be the best choice at another.

This issue is particularly important in operational hydrometric practice. If no universal forecasting model exists across stations, then model selection itself becomes a decision problem. In practice, analysts often compare several models and then choose the best-performing one for each site. That workflow is expensive and difficult to transfer to a new station. Previous studies also suggest that predictive performance depends strongly on site context, catchment setting and forecast horizon (Behzad et al., 2009; Guo et al., 2018; Bowden et al., 2002).

This study addresses the problem through a two-stage framework. First, we evaluate eight forecasting models for one-hour-ahead river water level prediction using Irish hydrometric data from a high-density network of 70 stations sourced from the Office of Public Works (OPW). Second, we reformulate the resulting evaluation as a leakage-free meta-learning task in which the aim is to recommend suitable forecasting models for unseen stations.

The contributions are threefold: a comparative evaluation of eight one-hour-ahead forecasting models across 70 Irish hydrometric stations; a leakage-free meta-learning formulation for station-aware model selection over a verified 11-model candidate archive; and a grouped leave- one-station-out evaluation protocol that reflects real-world deployment to unseen stations. We formulate hydrological model selection as a leakage-free meta-learning problem, enabling reliable recommendation of forecasting models for unseen monitoring stations.

STUDY AREA AND DATA

The study draws on hydrometric monitoring stations distributed across the Republic of Ireland, using a high-density network covering diverse hydrogeological conditions. To ensure balanced regional representation, the 70 stations selected for the forecasting evaluation were stratified across seven basin-region groups: Shannon, South Eastern, Western, Eastern, South Western, North Western and Neagh Bann. All observations were sourced from the Office of Public Works (OPW) hydrometric network.

Ten stations were drawn from each basin-region group, yielding 70 stations in total for the forecasting evaluation. Water-level series were recorded at 15-minute intervals and used to con- struct one-hour-ahead prediction samples spanning the period 2017 to 2022. This stratification allows the framework to account for varying catchment response times—from the larger, slower systems of the Shannon basin to the flashier, more responsive catchments in the East. The fore- casting stage relies exclusively on historical water-level observations as model input, isolating the predictive contribution of temporal dependence in the level series.

The second-stage meta-learning experiment was constructed from a derived meta-dataset comprising 154 station–model records drawn from 14 stations and 11 candidate models: Baseline, Linear, Dense, Conv, RNN, GRU, LSTM, LSTM Attention, Autoencoder, Transformer and VariationalAutoencoder. This candidate archive is broader than, and not identical to, the eight- model set evaluated in the forecasting stage (Table 1). Each record integrates temporal summary statistics derived from the water-level series, spatial and hydrogeological descriptors (including location, geology and soil variables), and static candidate-model descriptors available prior to model evaluation. Validation and test performance variables were deliberately withheld from the meta-learning feature set to preclude target leakage.

METHODOLOGY

FORECASTING EVALUATION

The first stage of the study evaluated eight candidate forecasting models: Baseline, Linear, Dense, MultiDense, CNN, RNN, GRU and LSTM. The task was one-hour-ahead river water level prediction using only prior water-level observations as input. This univariate setup was adopted deliberately, so that any differences in predictive performance across models and stations reflect the models' capacity to exploit the temporal structure of the level series rather than differences in input availability.

Each station dataset was partitioned into training, validation and test subsets using a strict chronological split, ensuring that model evaluation always occurred on observations recorded after the training period. Model performance was assessed primarily using Mean Absolute Error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i|$$

where *n* is the number of samples, *yi* is the observed level, and *ŷi* is the predicted value. Both validation and test results were examined across stations. The central question motivating this stage was whether any single forecasting model performs consistently well across all stations, or whether optimal model choice is station-dependent.

LEAKAGE-FREE META-LEARNING

The forecasting evaluation revealed that no single model dominated uniformly across all stations, which framed a natural second-stage question: can station-level contextual information be used to recommend the most suitable forecasting model for a previously unseen site, without access to any post-training performance data?

Two meta-learning formulations were considered:

- **Candidate ranking**: each record represents a station–model pair, and the target variable indicates whether that candidate is the best-performing model for the corresponding station. This formulation produces a ranked shortlist of models for each new station.
- **Station-level multiclass classification**: a single record is retained per station, with the target being the identity of the best model directly. This serves as a simpler, single-output comparison.

In both formulations, the best model at a station was defined as the candidate achieving the lowest held-out test MAE. To quantify the cost of an imperfect model recommendation, we define **performance regret** (*R*) as:

$$R = MAE_{selected} - MAE_{optimal}$$

where $MAE_{selected}$ is the error of the model recommended by the meta-learner, and $MAE_{optimal}$ is the lowest available test error at that station.

The candidate-ranking formulation was designated the primary experiment. By operating at the station–model level rather than the station level, it makes fuller use of the available meta-data and exposes the top-k behaviour of the recommender, which is more informative for operational deployment than a single predicted label.

A key design requirement was the prevention of target leakage. Post-training performance variables - including validation loss, validation MAE, held-out test MAE and execution time - were excluded entirely from the feature set. Only descriptors available prior to model training were retained, namely temporal summary statistics, spatial and hydrogeological descriptors, and static candidate-model characteristics.

Generalisation to unseen stations was assessed using a grouped leave-one-station-out evaluation protocol. For each fold, all records associated with the held-out station were withheld from training and reserved exclusively for testing. This grouped splitting strategy is substantially more stringent than row-level random splitting and more faithfully represents the operational scenario in which a recommendation must be made for a station with no prior performance history.

SYSTEM ARCHITECTURE

Figure 1 illustrates the complete two-stage workflow. Hydrometric observations enter the pipeline and pass through the station-level forecasting evaluation, producing station-specific

performance profiles for each candidate model. These profiles are then combined with temporal, spatial, hydrogeological and static candidate-model descriptors to construct the leakage-free meta-learning stage. The pipeline terminates with a ranked recommendation of candidate forecasting models suitable for deployment at a previously unseen station.

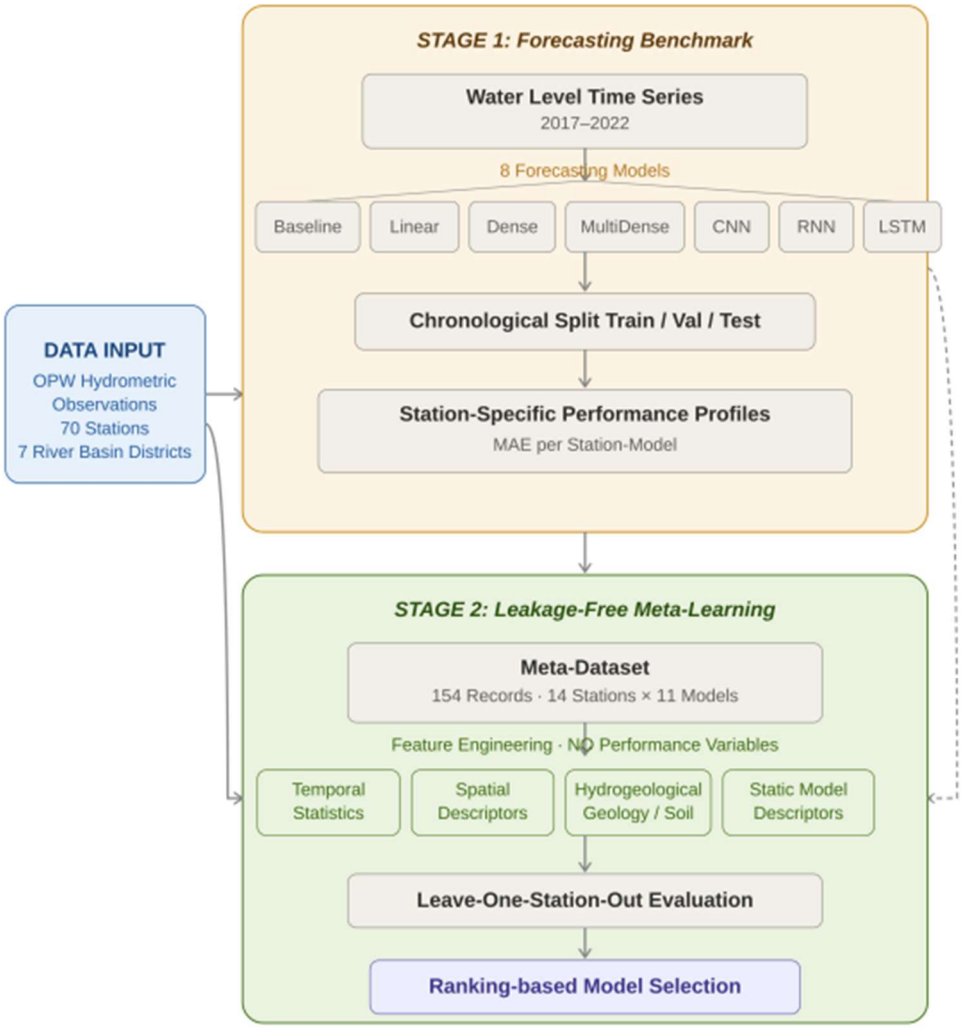

Figure 1: *System architecture of the two-stage forecasting and model-selection framework.*

RESULTS

FORECASTING EVALUATION

The forecasting evaluation confirmed that recurrent neural architectures, particularly LSTM and GRU, frequently produced the strongest predictive performance across the station network, while simpler model - Baseline, Linear and Dense - were generally unable to match them. Importantly, however, the results also revealed meaningful station-level variation: several stations favoured CNN, RNN or MultiDense over the leading recurrent models, confirming that model choice is location-dependent and that no single architecture is universally optimal across the Irish hydrometric network.

Table 1 reinforces this station-level picture. LSTM and GRU together account for 55 of the 70 best-performing cases, yet the remaining 15 stations are distributed across CNN, RNN and MultiDense. This distribution illustrates that a fixed single-model strategy would fail to capture meaningful local variation and motivates the station-aware model selection approach developed in the second stage.

Table 1: *Summary of the forecasting evaluation across 70 stations. Best-count indicates how often each model achieved the lowest test MAE at station level; Best MAE and Worst MAE report the corresponding extremes observed across all stations.*

Model	Best-count	Best MAE	Worst MAE
Baseline	0	0.0256	1.1624
Linear	0	0.0256	1.0608
Dense	0	0.0283	1.1149
MultiDense	3	0.0055	0.2652
CNN	6	0.0067	0.3113
RNN	6	0.0028	0.2475
GRU	26	0.0026	0.2760
LSTM	29	0.0025	0.2820

META-LEARNING RESULTS

The leakage-free meta-learning results are summarised in Table 2. Under leave-one-station-out evaluation, the candidate-ranking formulation placed the true best forecasting model within its top two recommendations for 10 of the 14 held-out stations, yielding a top-2 accuracy of 0.714. The top-1 accuracy was 0.571, indicating that the exact best model was identified for 8 of the 14 unseen stations.

The mean rank of the true best model across held-out stations was 2.071, with a median rank of 1.0, demonstrating that the optimal candidate was typically positioned at or near the top of the ranked list. The mean regret in held-out test MAE was 0.001206, with a median of 0.0, indicating that even in cases where the top-ranked recommendation was not the exact best candidate, the selected model performed at near-optimal levels. This low-regret behaviour is further illustrated in Figure 2, where the two MAE curves remain closely aligned across almost all held-out stations.

The station-level multiclass baseline also yielded competitive results, with an accuracy of 0.643, balanced accuracy of 0.747 and macro F1 of 0.674. Nevertheless, the candidate-ranking formulation remains the more operationally informative approach: it produces a ranked short- list rather than a single predicted label, exposes top-k behaviour, and supports regret-based evaluation that directly quantifies the cost of an imperfect recommendation in terms of held-out predictive error

Table 2: *Leakage-free meta-learning results under leave-one-station-out evaluation.*

Metric	Value
Ranking top-1 accuracy	0.571
Ranking top-2 accuracy	0.714
Mean true-best rank	2.071
Median true-best rank	1.000
Mean regret in test MAE	0.001
Median regret in test MAE	0.000
Station-level accuracy	0.643
Station-level balanced accuracy	0.747
Station-level macro F1	0.674

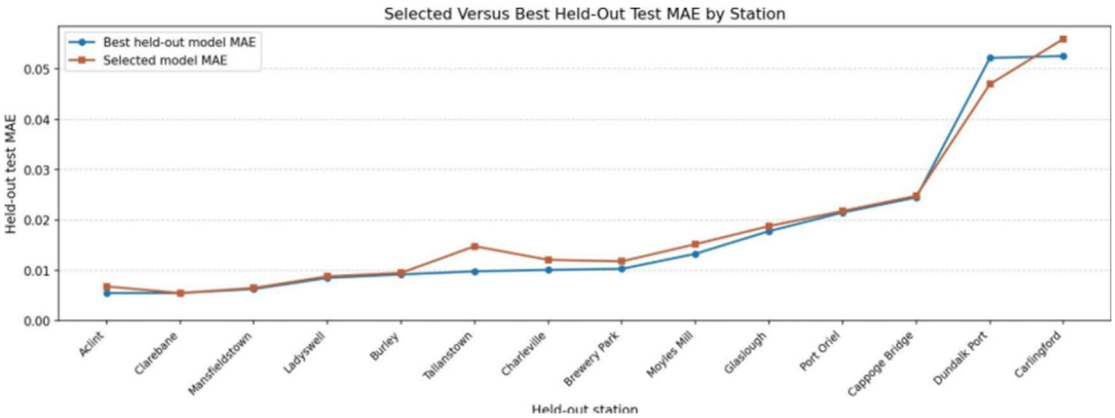

Figure 2: *Held-out test MAE for the selected model and the best available model at each station under leave-one-station-out ranking evaluation. The consistently narrow vertical separation between the two curves reflects the low mean regret of the ranking framework.*

DISCUSSION

Three principal observations emerge from this study. First, recurrent neural architectures are strong candidates for one-hour-ahead river water level prediction across the Irish hydrometric network, yet no single model performs consistently best at every station. Second, this station-level variability is sufficiently pronounced to justify treating model selection as an explicit and integral component of the operational forecasting workflow, rather than a secondary implementation detail. Third, a leakage-free meta-learning layer can generate ranked model recommendations for previously unseen stations, provided the meta-learning target is defined consistently from held-out test MAE. This reinforces the need to treat model selection as a first-class problem in hydrological forecasting rather than a secondary evaluation step.

From an operational hydrology perspective, the most informative result is not top-1 accuracy in isolation, but the combination of top-2 accuracy and low regret. A top-2 accuracy of 0.714 indicates that the framework reliably narrows the candidate space to two plausible models for a new station, substantially reducing the evaluation burden on practitioners. The mean regret of 0.001206, reinforced by the closely aligned curves in Figure 2, demonstrates that even when the top-ranked recommendation is not the exact optimal choice, the selected model performs at near-optimal levels. The framework should therefore be understood as a principled shortlisting tool rather than a hard single-model classifier - a distinction that matters for how its outputs are used in practice.

The two-stage architecture also addresses a methodological conflation that is common in applied forecasting studies: the question of how well a model performs at a given station is distinct from the question of how a practitioner should select among competing models for a new site. Separating these two questions explicitly improves the interpretability of the overall workflow and makes the approach more tractable to translate into operational hydrometric practice.

CONCLUSIONS AND FUTURE WORK

This paper presented a two-stage framework for river water level prediction and station-aware model selection across the Irish hydrometric network. In the first stage, eight forecasting models were evaluated for one-hour-ahead prediction across 70 stations, establishing that recurrent neural architectures—particularly LSTM and GRU—frequently achieve the strongest performance, while also confirming that no single model is universally optimal across all stations.

In the second stage, the forecasting evaluation was extended into a leakage-free meta-learning framework designed to recommend suitable candidate models for previously unseen stations. Under grouped leave-one-station-out evaluation over 11 candidate models, the ranking-based approach achieved a top-1 accuracy of 0.571 and a top-2 accuracy of 0.714,

with a mean regret of 0.001206 in held-out test MAE. These results demonstrate that meaningful model recommendations can be generated for unseen stations without recourse to post-training performance information, and that the recommended models are typically near-optimal even when they are not the exact best available candidate.

The central implication for Irish hydrometric practice is that station context carries actionable information for model selection. Treating model selection as an explicit stage of the forecasting workflow - rather than resolving it informally or retrospectively - improves both the transparency and the transferability of predictive systems across the network.

Future work includes expanding the meta-dataset to encompass a greater number of stations and regions; harmonising the candidate model set across the forecasting and meta-learning stages; enriching the feature space with additional catchment descriptors; incorporating hydrometeorological inputs such as rainfall and temperature; and developing uncertainty-aware ranking strategies for deployment in data-scarce settings. Overall, the results demonstrate that leakage- free meta-learning provides a practical and scalable pathway for context-aware deployment of forecasting models in heterogeneous hydrometric networks.

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Early Career Hydrogeology Awards 2026

RANK	NAME	INSTITUTION
First	**Niladri Chowdhury**	*TCD*
Second	**Anna Horvath**	*GSI*
Third	**Eimear Prendergast**	*TCD*

FIRST PRIZE

Hydrogeological and water quality investigation for vulnerability of karst groundwater systems to contamination by on-site wastewater effluent

Niladri Chowdhury, Patrick Morrissey, David O'Connell and Laurence Gill

Trinity College Dublin

Karst aquifers pose significant challenges in terms of trying to model the groundwater flow discharging from their springs due to their complex hydrogeological structure. The challenges are further exacerbated when it comes to the investigation and simulation of the vulnerability of such aquifers to contamination from different land-use practices. The study area is in west of Ireland, County Clare which consists of the Gort and Fergus River catchment. Most households in this rural catchment use on-site domestic wastewater treatment systems (OSWTS), predominantly septic tanks, and a combination of poor design, installation and lack of maintenance of these systems is contaminating the groundwater, as well as contamination from agricultural sources. The total catchment size is approximately 380 km^2 which consists of 10 monitoring sites including 3 karst springs and 7 river sites. Hydrological data (hourly water flow) has been collected by flow gauging and continuous water level monitoring, in addition to hourly rainfall data collected on the catchment. Specific water quality parameters have been used to separate the contamination from human wastewater effluent (versus agricultural sources) which are fluorescence whitening compounds (FWC), Tryptophan like fluorescence (TLF), E.coli, and Pepper mild mottle virus (PMMoV). Total Organic carbon (TOC), turbidity, chloride, and electrical conductivity (EC) have also been measured. To study the spatial and temporal variation of these parameters, sampling was carried out every month as grab sampling at the major karst springs on the catchment. In parallel, different sensors have been used for continuous hourly concentration measurement of TLF, turbidity, and EC. InfoWorks ICM software has then been used to build a numerical pipe network model of the catchment to simulate hydrology and contaminant transport, in conjunction with machine learning algorithms. Results until now showed clear evidence of groundwater contamination from OSWTS on the karst springs.

SECOND PRIZE

Assessing streamflow depletion in Irish Hydrogeological Settings

Anna Horvath and Katie Tedd

Geological Survey Ireland, Booterstown Hall, Booterstown, Dublin

A challenge from the recent introduction of the 2022 Water Environment Act is the management of streamflow depletion – where groundwater pumping captures water that would otherwise discharge into rivers or induces the infiltration of surface water into aquifers. The alteration of streamflow is especially critical to understand during low flows which depend on groundwater baseflows contributions. Streamflow depletion is difficult to measure directly in the field therefore, currently the most adopted method is to use analytical solutions which approximate the amount of water captured from nearby streams as a result of pumping. These approaches are valuable as an initial screening tool, but they rely more on simplifying assumptions than numerical models, which may limit their applicability. Building on the work of Zipper (2019) we combine analytical depletion functions with apportionment equations. In a case study we assess (a) the impact of groundwater abstraction from multiple wells and (b) the cumulative impact of the abstractions on the surface water body. Our results predict streamflow depletion fractions of up to 92% of the pumping rate and a reduction in the mean river flow of approximately 3 - 6%. During low flow conditions we project the Q95 flow decreases by approximately 30% 200 m downstream of the abstraction and by 3.5% 1.6 km downstream of the abstraction. Furthermore, this approach allows for identifying the most impacted stream segments and calculating the length of altered river flow. This approach provides a practical and accessible method for assessing groundwater abstraction impacts in Irish hydrogeological settings.

THIRD PRIZE

Spatial and Temporal Variability of $\delta^{18}O$ and $\delta^{2}H$ in Irish Precipitation

Eimear W. Prendergast[1,2], Conor J. Smith[1,2], Alex Cabral[1,2], David O Connell[3], Lawrence Gill[3] and Carlos Rocha[1]

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Stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) of precipitation have been widely used to understand and trace hydrological processes. Ireland has a long history of recording the isotopic composition of precipitation at the GNIP (Global Network for Isotopes in Precipitation) stations at Armagh and Valentia Island, with some single location studies.

However, the extent and drivers of spatial variability of isotopes across the country are still unclear. Studies of groundwater recharge sources and dynamics are therefore limited by a lack of knowledge of Irish isotopic precipitation inputs. This study addresses this gap by describing the spatial and seasonal variability of stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) in precipitation across Ireland and discussing its primary drivers.

Here we report on the first isoscapes of $\delta^{18}O$ and $\delta^{2}H$ in precipitation in Ireland. Samples were collected across the Republic of Ireland from May 2022 to July 2024 on monthly and daily timescales and analysed using Cavity Ring Down Spectroscopy (CRDS). We observed a southwest to northeast depletion gradient in both $\delta^{18}O$ and $\delta^{2}H$, with stronger spatial variability occurring in the wetter months. Local meteoric water lines differed significantly across sampling locations. On the basis of multilinear regression and principal component analysis (PCA) latitude is shown to be the dominant driver of variance of $\delta^{18}O$ and $\delta^{2}H$ in Irish precipitation. This study shows that Irish precipitation is not isotopically homogenous, and therefore future hydrogeological applications and modelling require more regionally resolved isotope inputs.

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