# Groundwater & Nature Based Solutions

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS - Irish Group

Proceedings of the 44th Annual Groundwater Conference

Tullamore Court Hotel, 16th and 17th April 2024

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

*Presents*

# Groundwater & Nature Based Solutions

Proceedings of the 44th Annual Groundwater Conference

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## INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH GROUP)

**Introduction**

Founded in January 1976, the IAH-Irish Group 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 (currently held in Tullamore), an annual weekend fieldtrip, and a series of monthly lectures and technical meetings. Funding for the association is derived from membership fees and the annual conference. 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 which are now housed in the Geological Survey of Ireland Library, 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 by contributing to the Geological Survey of Ireland's Groundwater 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).

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| For more information please refer to: | www.iah-ireland.org |
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# 2024 IAH (Irish Group) Conference **Groundwater & Nature Based Solutions**

It gives me great pleasure, on behalf of all of us on the organising committee, to welcome you to the 44th annual IAH Irish Group Conference. Your continued involvement and support of the IAH Irish Chapter is invaluable.

The theme of the conference this year is *Groundwater & Nature Based Solutions*.

Nature Based Solutions is an approach that promotes nature as a means for providing solutions to climate mitigation and adaptation challenges, and the concept is at the core of EU policies and frameworks. There are numerous definitions and meanings of the concept, but fundamentally it is about linking positive outcomes for society with the notion of nature as a means of achieving the outcomes (Nesshover *et al* 2017).

How we manage extreme events (floods and droughts), how we manage groundwater in urban areas or in undisturbed upland peats, how we think about groundwater in coastal zones requires using skills across numerous disciplines; and hydrogeologists are used to working with these multifunctional systems in resolving water management issues. This approach to strengthening water-resource resilience can be increased by diversifying management strategies. Green solutions, such as peatland management, restoration and preservation, and grey solutions, such as increasing supplies (desalination, wastewater reuse, managing coastal supplies), enhancing storage in surface reservoirs and depleted aquifers, and transporting water are all aspects of NBS (Scanlon *et al*, 2023).

The experiences, skills and training we have developed will be invaluable in getting the best results out of NBS, and can help address human and ecosystem needs while building resilience.

Presenters at the conference offer practical perspectives and experiences on issues related to groundwater – covering case and site studies, as well as insights into complexities of groundwater behaviour in particular environments (river channels and floodplains, urban settings, coastal and near shore zones); others will offer insights from deep systems, from peatlands, and from the machine learning perspective that will be invaluable to practitioners in Ireland and overseas.

The early career hydrogeologists show how our science is growing and developing to meet future needs, and the keynote speakers (Minister of State Malcolm Noonan TD, and Dr Catherine Farrell) provide the conference framing contexts.

The organising committee wishes to express their gratitude to all of those attending this year's conference, and conferences in previous years, and we extend a huge thanks to all of the speakers. We hope you find the conference interesting, educational and thought provoking.

Tiernan Henry
IAH (Irish Group)
Conference Secretary

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Scanlon, B.R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R.Q>, Jobbagy, E., Kebede, S., Koluso, S.R., Konikow, L.F., Long, D., Mekonnen, M., Müller Schmied, H., Mukherjee, A., MacDonald, A., Reedy, R.C., Shamsudduha, M, Simmons, C.T., Sun, A., Taylor, R.G., Villholth, K.G., Vörösmarty, C.J. & Zheng, C. (2023) Global water resources and the role of groundwater in a resilient water future. *Nature Reviews: Earth Environment* **4**, 87–101 https://doi.org/10.1038/s43017-022-00378-6

## 2024 IAH (Irish Group) Committee:

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For more information and contact details please refer to: *www.iah-ireland.org*

Cover Photo Credit: Tiernan Henry, University of Galway - Peat pipe flow, Letterunshin, Co Sligo

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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 to organise the conference:

**Groundwater & Nature Based Solutions**

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co Offaly
Tuesday 16th April – Wednesday 17th April 2024

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## Programme Day 1: Tuesday 16th April

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| 08:30 – 09:30 | Conference Registration: tea, coffee & exhibits |

**INTRODUCTION**

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|---|---|
| 09:30 – 09:45 | Welcome: Gerry Baker (*President IAH Irish Group*) |

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| **SESSION I** | |
| 09:45 – 10:15 | **KEYNOTE 1**: Minister of State Malcolm Noonan TD |
| 10:15 – 10:45 | **KEYNOTE 2**: Dr Catherine Farrell (Trinity College Dublin): *Peatland Restoration: A Nature Based Solutions* |
| 10:45 – 11:00 | *Q&A* |
| 11:00 – 11:30 | *Tea & Coffee* |

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| **SESSION II** | **Nature Based Solutions** |
| 11:30 – 11:50 | Peter Glanville (SLR Consulting Ireland): *Groundwater Dependent Terrestrial Ecosystems: River Channels and Floodplains, the importance of Physical Processes and Nature Based Solutions in the restoration of our river's biodiversity* |
| 11:50 – 12:10 | Sarah Collins (British Geological Survey): *Modelling the effectiveness of trees for flood risk reduction* |
| 12:10 – 12:30 | Patrick Morrissey (Trinity College Dublin): *Groundwater &NBS: Water 4All* |
| 12:30 – 12:45 | *Q&A* |

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| *13:00 – 14:00* | *Buffet lunch in Tullamore Court Hotel* |

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| **SESSION III** | **Coastal & Alluvial Deposits** |
| 14:00 – 14:20 | Ray Flynn (Queen's University Belfast): *Irish Alluvial Deposits: A sustainable water source, or not?* |
| 14:20 – 14:40 | David Ball (Hydrogeologist): *Ireland's Links Golf Courses - successful provision of fresh water irrigation supplies from sands and gravels next to the coast - Part 1* |
| 14:40 – 15:00 | Richard Langford (Parkmore Environmental Services): *Ireland's Links Golf Courses - successful provision of fresh water irrigation supplies from sands and gravels next to the coast - Part 2* |
| 15:00 – 15:20 | **Early Career Award Winner**: Hilary Pierce (University of Galway) *REWET: Hydrologic impacts of water table management on grassland peat soils* |
| 15:20 – 15:35 | *Q&A* |
| 15:35 – 16:00 | *Tea & Coffee* |

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| **SESSION IV** | **Groundwater Challenges** |
| 16:00 – 16:20 | Carlos Rocha (Trinity College Dublin): *Quantitative overview of the contribution of SGD to coastal primary production at the global scale* |
| 16:20 – 16:40 | Hannah Lehnhart-Barnett (University of Galway): *Testing-the-waters: Prediction of high flow events in blanket bog catchments using Support Vector Machines (SVM) for automated event water sampling* |
| 16:40 – 17:00 | Auke Barnhoorn (TU Delft): *A Research and Energy Production Geothermal Project On The TU Delft Campus: Project Implementation And Initial Data Collection* |
| 17:00 – 17:20 | Vicky Preece (Queen's University Belfast): *Nature based solutions – Overcoming the challenges of collecting reliable baseline data in remote environments* |

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| 17:20 – 17:35 | *Q&A* |
| 17:35 | *Posters & Wine Reception* |
| 19:00 | *Social event sponsored by IAH – Irish Group* |

## Programme Day 2: Wednesday 17th April

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|---|---|
| 08:30 – 09:30 | Conference Registration: tea, coffee & exhibits |
| **SESSION V** | **Peatland** |
| 09:30 – 09:50 | Francis Makin (RPS Ireland): *Peatland restoration in Ireland: a powerful nature based solution* |
| 09:50 – 10:10 | Laurence Gill (Trinity College Dublin): *Peatland restoration: ongoing research* |
| 10:10 – 10:30 | Bryan McCabe (University of Galway): *Embankments over Blanket Peat in County Donegal: Interpretation of piezometer data* |
| 10:30 – 10:50 | Duncan Dodge (WSP): *Natural Source Zone Depletion: Learnings from Field Scale Assessment on an Operational Facility* |
| 10:50 – 11:05 | *Q&A* |
| 11:05 – 11:30 | *Tea & Coffee* |
| **SESSION VI** | **Final Session** |
| 11:30 – 11:50 | **Early Career Award Runner Up**: Keith Harlin (Geosyntec Consultants): *Hydrogeologists make excellent Geothermal Geologists* |
| 11:50 – 12:10 | Berry Lyons & Anne Carey (The Ohio State University): *"Urban Karst" & the impacts of leaky pipes on groundwater & river chemistry* |
| 12:10 – 12:30 | Bruce Misstear (Emeritus Trinity College Dublin): *Wells and Wellbeing: Writing a book about holy wells in Ireland* |
| 12:30 – 12:45 | *Q&A* |
| 12:45 | *Conference Closing Address: Tiernan Henry (Conference Secretary – IAH Group)* |
| 13:00 | *Buffet lunch in Tullamore Court Hotel* |
| 14:30 – 16:00 | *Possible Exhibitor Demonstrations (to be confirmed)* |

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**SESSION V: Peatland**



**SESSION VI: Final Session**



**POSTERS**

# SESSION I

# PEATLAND RESTORATION: A NATURE BASED SOLUTION

**Catherine A. Farrell,** *Trinity College Dublin, Dublin 1.*

## ABSTRACT

*Nature-based solutions, as a concept, has been in development over the last twenty years. While definitions and perspectives vary depending on perspectives and goals, the concept essentially presents a framing for efforts to apply eco-technology, using the benefits we derive from ecosystems as the vehicle to address societal challenges. Ecological restoration is fundamental to many nature-based solutions and there is a growing understanding of the role healthy ecosystems play in delivering wider societal benefits. As such, both nature-based solutions and ecological restoration should be mutually supportive. Peatlands deliver an array of services to people including control of water flows, water purification, climate regulation, and biodiversity. The continued flow of these services is important for human well-being. Peatlands in a degraded state are damaging to human well-being, and their restoration has been identified as a nature-based solution to a) stop further degradation and/or losses due to associated negative effects and b) deliver nature positive gains (from a human, societal perspective) for action on climate change, water regulation and biodiversity recovery. From an Irish perspective, peatland restoration can help deliver climate and biodiversity targets, as well as recovery of a number of water related services, each important for varying Irish sectoral targets. We need to work across disciplines in Ireland to help develop and deliver nature-based solutions, integrating ecological restoration and engineering disciplines to build on the strengths of both to deliver effectively for both people and nature.*

**Key words:** *Restoration, Nature-based Solutions, Climate, Water and Biodiversity co-benefits, Community engagement.*

## DEFINING NATURE BASED SOLUTIONS

The IUCN (International Union for Conservation of Nature) pioneered the concept of 'Nature-based Solutions' over 20 years ago, formulating a formal definition and then developing the IUCN Global Standard to inform the design, implementation and evaluation of interventions (IUCN, 2020). According to the IUCN definition: nature-based solutions (often abbreviated to NbS) are actions to address societal challenges through the protection, sustainable management and restoration of ecosystems, benefiting both biodiversity and human well-being (IUCN, 2020).

The European Commission defines nature-based solutions as solutions that are inspired and supported by nature, which are cost-effective, and simultaneously provide environmental, social, and economic benefits and help build resilience. Such solutions bring more and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient and systemic interventions (European Commission, 2016). Seeking to create novel eco-technologies and management practices, the EU approach aims to embed nature-based solutions in business models that sustainably capture and deliver value, offering a path to sustainable socio-economic development (Maes and Jacobs, 2015).

Both IUCN and European Commission definitions, while broadly similar (both share the overall goal of addressing major societal challenges through effective use of ecosystem and ecosystem services), have a few significant differences. IUCN's definition emphasises the need for a well-managed or restored ecosystem to be at the heart of any nature-based solutions, while the European Commission definition places greater emphasis on the practical, implementation phase, applying solutions that not only use nature, but are also inspired and supported by nature (UNEP, 2021).

The concept is still in refinement and in 2022, the United Nations Assembly adopted resolution 5/5, entitled "Nature-based solutions for supporting sustainable development”. The resolution provides the first multilaterally agreed definition of nature-based solutions’ as “*actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits*” (UNEA, 2022).

As definitions continue to be refined over time, reflecting changes in understandings of the role of healthy ecosystems for wider societal benefits, White *et al.* (2021), summarise approaches and highlight that nature-based solutions essentially present a framing for efforts to apply eco-technology, using the benefits we derive from ecosystems as the vehicle to solve problems. Work to date, especially through development of the IUCN global standard has served to establish best practice norms, management guidelines and governance structures (IUCN, 2020), while additionally improving our understanding of the relationship between ecosystem services, benefits and solutions (White *et al.*, 2021).

## ECOLOGICAL RESTORATION AS A NATURE-BASED SOLUTION

In terms of understanding the relationship between ecological restoration and nature-based solutions, there are also some nuances to tease out. Restoration is explicitly called out in the IUCN definition (along with protection and sustainable management (IUCN, 2020)), and while it is highlighted as integral to nature-based solutions (UNEP, 2022a); restoration is not assumed to be synonymous with nature-based solutions. Understanding the differences has important implications for purpose, plans and practices that shape societies and ecosystems (Waylen *et al.,* 2024).

The starting point of ecological restoration is to repair and restore an ecological system, or a part thereof, as illustrated by the Society of Ecological Restoration (SER) restorative continuum (Gann *et al.,* 2019). The starting point of nature-based solutions is generally societal needs and goals (IUCN, 2020). Furthermore, while ecological restoration can provide societal benefits, these may be co-, not core, benefits; whereas they should be the focal point from the framing of nature-based Solutions (Waylen *et al.,* 2024).

Nature-based solutions and restoration may therefore be considered as different entry points to a restoration / nature-based solution driven continuum; and at any point in time, a particular idea or initiative may be somewhere in between these concepts (Waylen *et al.*, 2024). However, there is much greater awareness of the societal benefits, which can be the outcome of both ecological restoration and nature-based solutions (Bullock *et al.*, 2021; Farrell *et al.,* 2022a), as summarised here:

*a) Restoration* has a focus primarily on specific ecological goals / outcomes; these in themselves, are ecological societal benefits, but can also deliver additional (side) societal co-benefits;

*b) Nature-based solutions* have a focus on a problem or issue, tapping into ecological processes to support a desired benefit, often with additional co-benefits for nature.

In practice, both framings should support each other. Given the scale of work required to address national and global biodiversity, water and climate challenges (Diaz *et al.,* 2019) synergies across frameworks for action (Gorman *et al.,* 2023), for both people and nature are essential. In this paper, peatlands present an example of how restoration provides a supportive framing for nature-based solutions, and vice versa, given the significant benefits delivered by bringing peatlands back to good health.

## UNDERSTANDING THE ROLE OF PEATLANDS IN REGULATING OUR ENVIRONMENT

## PEATLANDS AS NATURAL SUPPORT SYSTEMS

Healthy peatlands are wetlands, characterised by complex interactions between three main factors: water, biodiversity and peat. Tweak one of these components and we effect change in the living peatland system, making them more vulnerable to natural hazards and climate change at the same time, such as landslides (Long *et al*., 2011).

Peatlands have been regulating our climate for millennia and while globally peatlands cover only 3% of the Earth's land surface, they store about double the amount of carbon as in all forests (UNEP, 2022b), which cover ten times the area (30%). Healthy peatlands are wet, and the peat or carbon built up over time is stored safely in an anoxic environment. Draining a peatland allows microbes to break down peat, thereby switching it to a carbon source. Also, as the peat mass is dry, it becomes destabilised and more susceptible to fire and erosion (with knock on effects for further carbon losses and water regulation) (UNEP, 2022b).

Peatlands absorb water in high rainfall events (depending on their hydrological status), acting like sponges, slowly releasing that water over time back into watercourses. In this respect, they help control flooding and play integral roles for water regulation (Martin-Ortega *et al.,* 2014, 2021). Changes in weather patterns leading to intense flooding highlight the need for peatlands working in our catchments upstream to help 'slow the flow' and reduce impacts downstream (Farrell *et al.*, 2022a; Pschenyckyj *et al.,* 2021; Collier & Bourke, 2020).

From a biodiversity perspective, peatlands present an array of diverse ecosystems and species, with the component species (such as *Sphagnum* species, shrubs, algae etc.) helping to maintain and regulate the surface water level and consequent carbon balance. Due to intensification of land use changes elsewhere in the Irish landscape, increasingly rare species such as Curlew, Hen Harrier and Red Grouse rely on peatlands (NPWS, 2019) to sustain what remains of their populations.

In summary, healthy peatlands deliver an array of services to people: including control of water flows, water purification, climate regulation, and biodiversity (Bonn *et al.,* 2016); and the continued flow of these services is important for human well-being. However, change the water regime by draining, utilise peatlands for timber crops or wind farms, or dig out the valuable carbon stock, and we change the peatland, often switching peatlands from having benefits to creating a number of dis-benefits (Farrell *et al.,* 2022b).

Peatlands in a degraded state are damaging to human well-being, and their restoration has been identified as a critical Nature-based Solution (Bonn *et al.,* 2016) to a) stop further degradation and/or losses due to associated negative effects and b) deliver nature positive gains (from a human, societal perspective) for action on climate change, water regulation and biodiversity recovery.

## IRISH PEATLANDS: A CHANGING LANDSCAPE

Ireland is a global hotspot for peatlands; with over 20% of the national territory covered by peatland or peat soils (Connolly & Holden, 2009). Given their scale and integral role in the Irish landscape, peatlands are valuable ecosystems that form a significant part of the Irish socio-cultural landscape (Feehan & O'Donovan, 1996). There are four main types of peatland in Ireland: raised bogs, mountain and lowland blanket bogs, and fens, each with characteristic features that arise from their local climate and geography (Doyle & O'Críodáin, 2003).

Peatlands are wetlands. Lands that are wet are typically not suitable for highly productive farming and forestry practices. Because of this, peatlands and their associated habitats, have been traditionally viewed as unproductive or wastelands. This led to ongoing efforts, concentrated in the last century, to drain and transform them into 'good land' to be used for fuel, farming and forestry (Connolly, 2018). In recent decades, the extensive space provided by peatlands has also made them attractive for large-scale wind energy projects (Renou-Wilson & Farrell, 2009).

Over a quarter of the total area of peatland in Ireland has been drained for grassland, about a third developed for forestry and a significant portion of the raised bogs converted to industrial extraction (ca 5% of the total peatland area). The remaining areas comprises commonages, and turbary areas (Connolly, 2018), scarred by centuries of turf cutting. Most of these areas are today, acting as sources of carbon dioxide, as well as contributing to poor water quality and loss of biodiversity (Pschenyckyj *et al.*, 2021).

Our activities have changed peatlands: with few pockets of healthy peatlands left in Ireland. The desolate and barren industrial *bog-scapes* of the midlands, recent bog slides in Leitrim, Donegal and Kerry in 2020 and - despite being priority and listed habitats under Annex I of the EU Habitats Directive - peatlands within the Natura 2000 network continue in Bad conservation status (and declining) (NPWS, 2019).

## IRISH PEATLANDS: TIME TO RESTORE

The balance struck in a healthy peatland allows it to store vast volumes of carbon and water. Every peatland is different and successful restoration requires an understanding at site and catchment level (Farrell et al., 2022b). Passive rewilding is not an option for peatlands, and active restoration measures are required (Mackin *et al.,* 2017a). This often involves engineering solutions, underpinned by expert hydrological assessment given that often the key aspect is how to rewet a peatland (Mackin *et al.,* 2017a, b). Over-arching principles of peatland restoration can be summarised as follows (though for a comprehensive framework follow the SER Guidance (Gann *et al.,* 2019)):

i) *Engage*: co-design and implementation alongside comprehensive and continual stakeholder engagement with relevant stakeholders, national to local, from start to finish (as outlined in Principle 1 of the SER Restoration Principles (Gann *et al.,* 2019)), is critical to the success of any restoration.
ii) *Understand*: identify the extent and condition of the peatland, as well as pressures and threats (past and present), assess the likelihood of successful restoration using available information (scientific and local);
iii) *Stabilise*: reduce the effects of and/or cease identifiable degradative activities which are impacting on the peatland (such as drainage, planting, cultivation, burning);
iv) *Reverse degradation*: this generally involves hydrological manipulations such as blocking drains, along with activities such as re-profiling peat banks and dry edges;
v) *Restore*: while it will not be possible to restore most peatlands to their original state (Farrell & Doyle, 2003), restoring functional aspects of peatlands allows for recovery of key ecosystem services while putting the peatland back on a trajectory towards good health;

Successful peatland restoration requires a multi-disciplinary approach with hydrologists, geomorphologists, ecologists and increasingly, social scientists playing a key role. The latter involvement of the social sciences reflects the need to involve stakeholders, and local communities in particular, in the restoration process and design. Peatland restoration involves a shift in behaviours and attitudes towards wetlands. Stakeholder engagement is essential to assist in changing attitudes towards peatlands, and local communities will play a central role in sustainable management post restoration (Flood *et al*., 2021; Martin-Ortega *et al.,* 2021).

## IRISH PEATLANDS: SCALING UP *JUST TRANSITION*

In terms of direct Irish experience, seminal work initiated by Dutch researchers in the 1980s in partnership with the National Parks and Wildlife Service (NPWS) laid significant foundations for understanding raised bogs (Mackin *et al.,* 2017a). Since then, LIFE projects developed by the NPWS such as the Wild Atlantic Nature LIFE project, Coillte (EU LIFE projects completed in 2004 and 2007) and Bord na Móna continue to carry out targeted site level works.

In recent years, EIP projects such as the Hen Harrier, Pearl Mussel and FarmPEAT projects have been breaking new ground, engaging farming communities to alleviate pressures and encourage restorative measures. Environmental NGOs such as the BirdWatch Ireland, and in particular the IPCC, have contributed greatly to understanding the causes and approaches to restoration, and community groups across Ireland also getting involved. Research plays a significant role helping to guide restoration, address complex issues such as carbon reporting and scaling up restoration, and addressing knowledge gaps (Pschenyckyj *et al*., 2021).

Peatland restoration delivers returns in terms of carbon, water, biodiversity and human well-being (Andersen *et al*., 2017). This is evidenced increasingly across project sites such as the return of carbon sequestration at former industrially mined blanket bogs sites and restored midlands raised bogs (Wilson *et al*., 2012, 2022) and the co-benefits identified for water and biodiversity (Pschenyckyj *et al.,* 2021). Benefits for communities are also evident (Flood *et al.,* 2021) with enthusiasm shown in growing membership and restoration action supported by the Community Wetlands Forum.

Peatlands in the Irish landscape are unbounded; there are rarely fences or gates around them. Understanding how peatlands have been used, and how they have been changed through our activities – particularly over the last century - is essential to planning for their future; an approach that forms the basis for natural capital approaches trialled to prioritise peatland restoration at catchment scale in Ireland (Farrell *et al.,* 2022b).

Peatlands are multi-sectoral - with policies for agriculture, climate and energy, the environment, forestry, and nature and water management affecting their use. A multi-sectoral, trans-disciplinary approach to support changes in perspectives and in turn support both peatland restoration and peatland nature-based solutions is essential. This could be supported by the outcomes of the ongoing Land Use Review.

Creating a policy and economic structure to facilitate peatland restoration - a key action of *Just Transition* – identifying opportunities for public and private investment in activities that are both sustainable and inclusive is also necessary, an aspect currently explored through the Peatlands Finance Initiative.

## SUPPORTING NATURE BASED SOLUTIONS IN IRELAND

Peatland restoration is a critical and proven nature-based solution (Bonn *et al.,* 2016), resonating clearly with the UNEA 2022 definition, involving: "*actions to … restore, sustainably use and manage natural or modified … ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits*" (UNEA, 2022).

There is in an increasing number of documented examples of Irish nature-based solutions including those relating to river restoration (catchment management) (Collier & Bourke, 2020), dune restoration (coastal protection) (Lawlor & Jackson, 2021) and those addressing challenges in urban areas such as wastewater treatment, a particular focus for countries with increasing populations in urban areas (Collier *et al.,* 2023; UNEP 2021).

A recent review of nature-based Solutions carried out for the Climate Advisory Council in Ireland (Molloy *et al*., 2024) highlighted eight types of nature-based solutions active in Ireland relating to agroecosystems, integrated constructed wetlands, urban greening, rivers, peatlands, woodlands, wetlands and the marine, with urban greening solutions the most common type of nature-based solution identified. Delivering across an array of ecosystem services, all examples were contributing to either climate adaptation or mitigation (Molloy *et al*. 2024).

The report also identified a number of barriers to the implementation of nature-based solutions, which also echo true as barriers to the implementation of restoration in Ireland. These include limited funding and resources, a lack of information on implementation, a lack of evidence and published data on the effectiveness of nature-based solutions, and a lack of knowledge transfer from academics in this area to stakeholders wanting to apply these solutions (Molloy *et al*. 2024).

## CONCLUSIONS

Both ecological restoration and nature-based solutions are essential frameworks to deliver sustainable futures for people and nature. While ecological restoration delivers multiple benefits for society, these benefits are often over-looked from the societal benefit perspective - often viewed as a 'nice to have' - a view that is gradually changing, aided by the use of natural capital approaches and the realisation that healthy natural systems underpin society and economy (Farrell *et al.,* 2022b; Farrell & Daly, 2020).

Nature-based solutions help by highlighting solutions to immediately understood societal problems, integrating ecological restoration tools and approaches to deliver sustainable solutions. As highlighted in the case of peatland restoration, getting nature-based solutions from concept, to action, and tackling site-specific restoration challenges to realise over-arching opportunities and societal benefits, will only succeed through collaboration across sectors and disciplines: it's time to roll up the sleeves and get on with it.

## ACKNOWLEDGEMENTS

Thanks to colleagues from Trinity College Dublin for their insights and knowledge of the topic of nature based solutions (Siobhan Mc Quaid, Cian White, and Marcus Collier); as well as many peatland colleagues and friends for their insights over the past three decades. Last, but not least, thanks to the peatlands.

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# SESSION II

# GROUNDWATER DEPENDENT TERRESTRIAL ECOSYSTEMS: RIVER CHANNELS AND FLOODPLAINS, THE IMPORTANCE OF PHYSICAL PROCESSES AND NATURE-BASED SOLUTIONS IN THE RESTORATION OF OUR RIVER'S BIODIVERSITY.

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## ABSTRACT

*Rivers, including river channels and floodplains, are important Groundwater Dependent Ecosystems (GWDTE) and when functioning correctly they provide vital nature-based solutions for our society via a range of ecosystem services. Hydrology, flooding, sediment erosion, transport and deposition are all natural processes in our environment.*

*However, in the past c. 130 years changes in economic activity and the implementation of policy measures have meant that our river channels and floodplains have become severely degraded in terms of their hydromorphology, habitat and biodiversity.*

*Rivers in Ireland have been modified in the past for various reasons including power generation, to facilitate peat extraction, navigation, water supply, to mitigate flooding impacts and also for land drainage purposes. At present approximately 16,000 km of rivers have been modified under various drainage schemes and acts which are designed primarily to improve land for agriculture, through the mitigation of flooding, and the river channels continuously maintained for this purpose.*

*The hydromorphology of our rivers underpins and provides the physical structure or environment required for aquatic and riverine habitats and biodiversity. The hydromorphology is dependent on a range of catchment environmental factors, including geology, sediment availability, hydrogeology and hydrology. Rivers provide for both water and sediment flows; sediment transport including erosion and deposition are key parts of the river hydromorphology.*

**Key words:** *river channel, floodplain, Nature-based Solutions, hydromorphology, river restoration, biodiversity, EU Nature Restoration Law*.

## WHAT ARE NATURE-BASED SOLUTIONS?

The opportunities around Nature-based Solutions (NbS) have become a 'key' topic in the past couple of years. Various versions of NbS are being promoted as providing the solutions to many of the environmental problems we are facing today, particularly around the decline in biodiversity, flooding impacts, water quality and climate resilience.

The aim of NbS is to replicate natural processes and in doing so provide societal benefits to us. There are two general types of NbS; firstly, engineered NbS such as Sustainable Drainage Systems and Integrated Wetland Systems which are designed to mimic natural processes to control and treat water. The second type of NbS, which are discussed here, are around catchment scale processes to provide Ecosystem Services to us.

There are numerous definitions and infographics around NbS. However, the International Union for the Conservation of Nature has defined Nature-based Solutions as:

*'Nature-based Solutions (NbS) are actions to address societal challenges through the protection, sustainable management and restoration of ecosystems, benefiting both biodiversity and human well-being.'*[i]

## RIVER CHANNEL MODIFICATIONS

Government policy measures around our rivers has resulted in the decoupling of river channels from their floodplains in order to manage the flooding of lands and groundwater levels. This control of flooding and groundwater levels through channel modification has resulted in the river and associated wetland GWDTEs becoming degraded.

River intervention measures have controlled natural physical processes including flooding, erosion and deposition, in order to improve channel conveyance, reduce the frequency of flooding of land and control groundwater levels, particularly across the floodplains and wetlands adjacent to the river channels.

The implementation of certain government policy measures has meant that many of our river channels and floodplains are now in a degraded state in terms of their physical processes, particularly the hydromorphology which underpins habitats and biodiversity.

## RIVERS PROVIDE NATURE-BASED SOLUTIONS TO ADDRESS BIODIVERSITY LOSS

Biodiversity loss is one of the most pressing challenges facing us at a national, European and global scale, and in Ireland the restoration of our river channels and floodplains will be a significant step towards reversing this loss.

We are currently in a transition phase with regard to how we view and treat our environment. This transition requires a profound shift in how we consider, approach and set out our institutions to address the challenges from climate change, biodiversity loss and water requirements.

The primary focus for some time now has been around the protection of nature and our environment, which in many cases has meant maintaining the current status, or at best not making it any worse. However, there is now a shift in approach to the restoration of the environment to reverse biodiversity loss and we are moving toward a multidisciplinary catchment based approach to our rivers and environment. The recent evolution of relations between humans and our environment is shown in Figure 1.

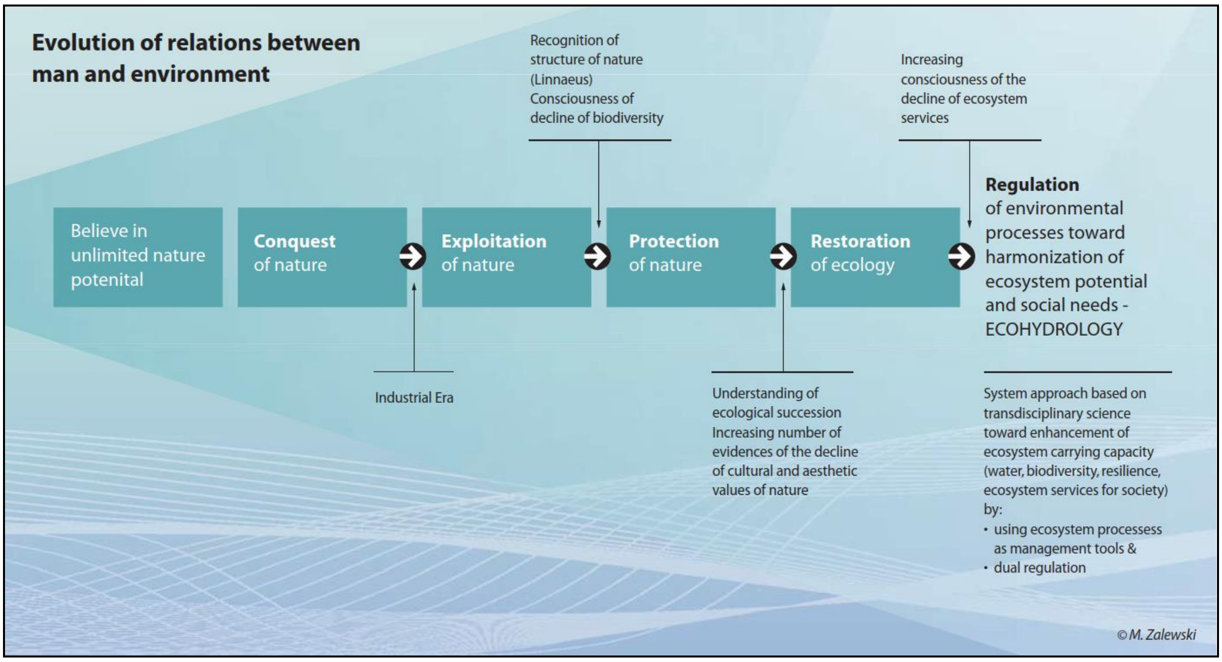


***Figure 1:*** *The evolution of relations between humans and our environment (after M. Zalewski, Source: International Hydrological Programme[ii])*

When the physical processes of our rivers are functioning correctly, river channels and floodplains provide ready NbS via vital Ecosystem Services for our society, covering biodiversity, flood mitigation, water quality and climate resilience.

The 2023 Citizens' Assembly Report on Biodiversity Loss[iii] provides a pathway for addressing biodiversity loss in Ireland. The report makes 14 recommendations in relation to freshwater environments (rivers and lakes) in Ireland and the government has committed to implementing all of the recommendations in the report.

In addition, the EU Nature Restoration Law[iv], part of the EU Green Deal for a climate neutral Europe by 2050, provides specific targets for the restoration of ecosystems. The restoration targets are at least 20% of land and 20% of sea areas by 2030, and all ecosystems in need of restoration by 2050. EU countries must restore at least 30% of habitat types covered by the new law that are in poor condition to a good condition by 2030, increasing to 60% by 2040, and 90% by 2050.

In order to implement the recommendations of the Citizens' Assembly report and achieve the targets set out in the Nature Restoration Law to address biodiversity loss we need to look carefully at restoring the physical processes of our rivers and recognise the vital Ecological Services that our rivers can provide to us as a society.

However, it will only be possible to address biodiversity loss in our rivers and floodplains if the physical catchment processes around flows, sediment erosion and deposition are addressed; it is these physical processes which form the basis of a functioning river and its habitats.

## THE RESTORATION OF MODIFIED CHANNELS

The objective for our modified rivers should be to attain Good hydromorphological status, or better, in order to provide sustainable freshwater habitats and to reverse biodiversity loss. The successful restoration of modified rivers will need to be underpinned by a functioning geomorphological system which promotes habitats and biodiversity at its core; if Good hydromorphological conditions are achieved then freshwater habitats will be created and enhanced biodiversity will follow as a consequence.

The restoration of our rivers has to date has primarily focused on instream restoration including historic weir removal to aid flows and restore fish passage, and also the creation of instream habitats to promote fish species.

The successful restoration of rivers will require a fundamental change in how we view our channels and floodplains. The river channel and floodplain is a natural phenomenon and a nature-based system where flows, flooding, sediment erosion, transport and deposition are all part of a natural processes.

## RIVERS AND FLOODPLAINS ARE A NATURE-BASED SOLUTION

In order to address biodiversity loss and with the implementation of the new EU Nature Law we need to look carefully at the ecological services that our rivers can provide to us as a society.

A functioning river system based on natural catchment processes is a NbS providing important ecosystem services to us, including increased biodiversity, climate resilience, flood mitigation, water resilience and functioning wetlands, all of which provide significant societal benefits.

Nature-based Solutions offers us a holistic ecosystem-based and catchment scale approach to implementing the recommendations of the Citizens' Assembly report, and in particular the restoration of the natural physical processes of the river channel, floodplain and wetland GWDTEs which takes into account the entirety of the hydrological cycle.

## SUMMARY

The restoration of our rivers and floodplains provides a nature-based approach addressing biodiversity loss, flooding impacts, water quality and climate resilience.

The Water Framework Directive provides us with the data on the condition of our surface water and groundwater, the Citizens' Assembly report provides the pathway to address biodiversity loss and the EU Nature Restoration Law sets the targets for river restoration in Ireland.

Recommendation no. 92 of the Citizens' Assembly report on Biodiversity loss states that '*The State must provide a single body to oversee and co-ordinate the many relevant bodies that manage, implement, and enforce legislation and policies relevant to freshwater*'. This statement recognises the number of government departments and agencies involved with our catchments and rivers, with overlapping remits and often competing aims, who involved in the management of our groundwater and surface water. The successful restoration of our rivers will require the coming together of all government agencies to co-ordinate a single catchment-based approach.

Given the benefits of river restoration it should not be viewed a binary choice for stakeholders; however, the environmental, social and economic benefits to our country of river restoration must be balanced against other land use requirements. One of the key aspects of river restoration is that the benefits will be spread across many stakeholders; in this respect, restoration does not, and indeed is not seen to, fall on one particular community or region within the State.

[1] International Union for Conservation of Nature - Issues Brief: Ensuring Effective Nature-based Solutions (July, 2020)

[1] UNESCO / Natural Sciences Sector Division of Water Sciences, International Hydrological Programme (2011). Biodiversity for Sustainability.

[1] Report of the Citizens' Assembly on Biodiversity Loss (March, 2023)

[1] www.europarl.europa.eu

# MODELLING THE EFFECTIVENESS OF WOODLAND PLANTING: EXAMPLES FROM THE COTSWOLDS, ENGLAND, AND THE EDDLESTON WATER, SCOTLAND

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## ABSTRACT
*Although tree planting is being promoted in the UK as an approach to tackling flooding, there remains limited evidence on its effectiveness. In recent years, the BGS has been modelling the impact of woodland planting in different landscapes. Here we present results from two contrasting catchments: the Upper Thames to Eynsham, a lowland catchment in southern England dominated by the permeable geology of the Cotswolds Hills; and the Eddleston catchment, a typical UK upland catchment located in the Scottish Borders with less permeable geology. We find that geology exerts a far larger control on flooding than land use. Models indicated that large-scale, and unrealistic, levels of coniferous woodland planting led to meaningful reductions in high flows in our lowland catchment, and this level of planting also had a detrimental impact on low flows. Modelling results from our upland catchment showed potential for flood peak reductions in autumn, but not in winter, with extensive coniferous or broadleaved planting. Woodland planting is most likely to be effective as a flood management measure in small catchments underlain by low permeable geology in summer or autumn.*
**Key words**: groundwater, catchments, flooding, rivers, forests

## INTRODUCTION
The desire to find nature-based solutions (NBS) to environmental problems (Cohen-Shacham et al., 2016; Faivre et al., 2017; Maes & Jacobs, 2017) has led to a growth in interest in natural flood management (NFM) for the reduction of flood risk. NFM is made very attractive by the range of co-benefits it entails: enhancing biodiversity, soil and water quality, and carbon sequestration as well as reducing soil erosion (Dadson et al. 2017). However, the effects of woodland planting on reducing flooding remain uncertain (Stratford et al., 2017), and are likely linked to a range of local factors, such as catchment size and soils and geology (Peskett et al., 2021), among others.
Here we present modelling work on the effectiveness of woodland planting in two contrasting settings: Eddleston, a small (69 km$^2$) upland catchment in the Scottish Borders; and the Upper Thames, a large (1616 km$^2$), lowland catchment. Whereas flooding in Eddleston occurs as a result of individual storm events; flooding in the Upper Thames is driven by high groundwater levels resulting from prolonged periods of wet weather.

## THE COTSWOLDS
The Thames to Eynsham (1616 km$^2$) is a groundwater-dominated, lowland catchment in southern England (Figure 1). The Thames runs west to east and is fed by tributaries from the Cotswolds Hills to the north, as well as several smaller clay subcatchments to the south. The catchment was one of those studied by the LANDWISE project

(https://landwisenfm.wordpress.com/about/), one of three projects funded by the Natural Environment Research Council (NERC) Natural Flood Management Research Programme.

***Figure 1**: Location of Thames at Eynsham catchment. From Collins et al. (2023)*

The Cotswolds Hills (up to 280 masl) dominate the catchment, dipping gently east−southeast towards the Thames floodplain (Neumann et al., 2003; Rushton et al., 1992). Land use within the catchment is predominately agricultural with a roughly equal split of arable (cereals) and grassland/improved grassland. Over the Cotswolds Hills, 11% of land use is broadleaved woodland and 1% coniferous. Long-term mean precipitation across the catchment is 757 mm/a, which mainly falls as rainfall (1951–2017, National River Flow Archive 2022).
The hydrology of the catchment is controlled by its geology (Bricker et al., 2014): an alternating sequence of Jurassic Limestones and clays. Two distinct aquifers separated by clays are present: the lower Inferior Oolite (IO) and upper Great Oolite (GO; Figure 2). Although distinct, the GO and IO are connected in places via faults (Maurice et al., 2008). As typical for the geology, the aquifers have low storage and high hydraulic conductivity (Morgan-Jones & Eggboro, 1981). Superficial deposits of sand and gravel are found on the Thames floodplain and extend up onto the hillsides (Bricker & Bloomfield, 2014). The aquifers are predominately overlain by shallow, freely draining soils (30–50 cm). More clay-rich soils are found towards the Thames floodplain, and locally along the river.

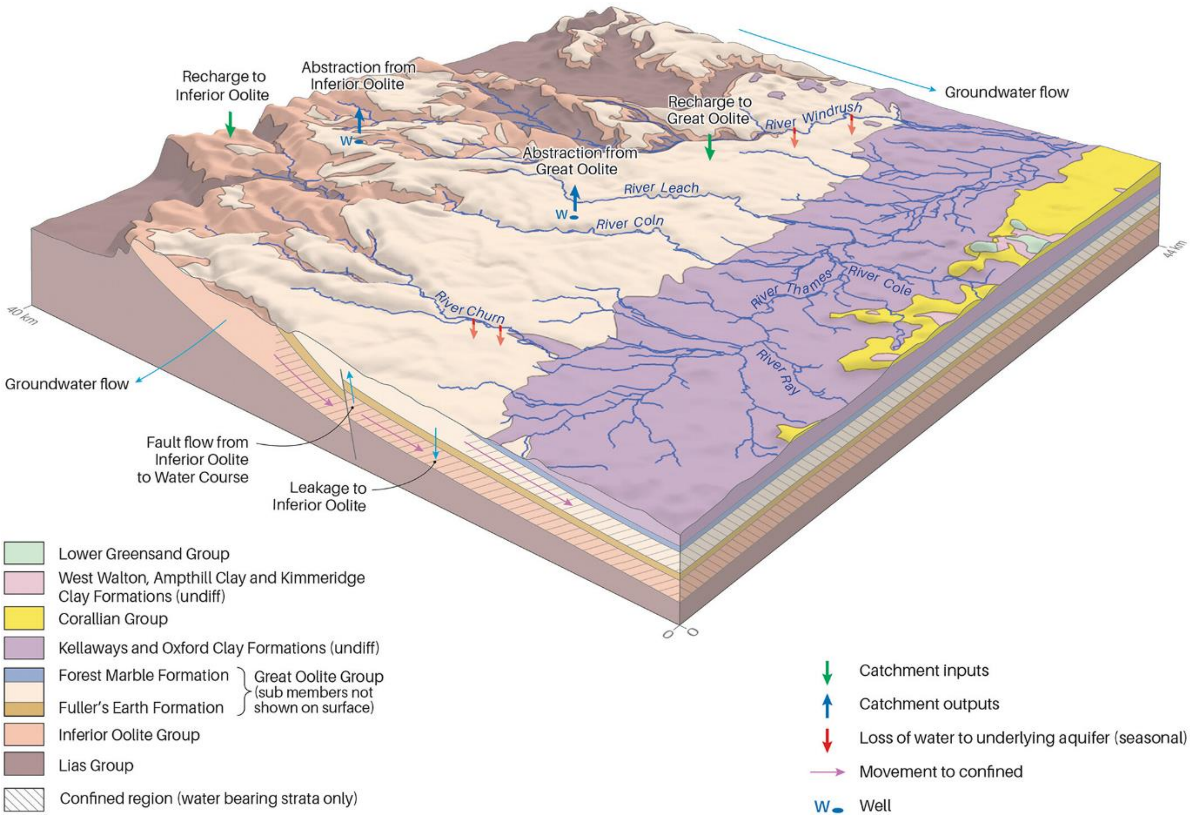


***Figure 2:*** *Schematic geology of the Upper Thames to Eynsham. From Collins et al. (2023)*

## THE EDDLESTON CATCHMENT

The Eddleston Water catchment (69 $km^2$) is a tributary of the River Tweed in the Scottish Borders, UK. The Eddleston Water flows due south and is fed by several distinct subcatchments (Figure 1). The catchment is host to the Scottish Government's long-term study on the effectiveness of NFM measures to reduce flood risk to downstream communities and improve habitats for wildlife. The project is a partnership initiative led by Tweed Forum (a local non-governmental organisation), with the Scottish Government, the Scottish Environment Protection Agency (SEPA), the University of Dundee, the British Geological Survey and Scottish Borders Council (Black et al. 2021).

Catchment characteristics are typical of much of the UK uplands. Topography is in the range of 180-600 m (Figure 1), mean annual precipitation is ~900 mm, falling mainly as rainfall, and monthly mean temperatures range from 3 to 13 °C. Land cover is mainly improved or semi-improved grassland on the lower slopes, rough heathland at higher elevations and marshy ground in the hollows. Extensive coniferous plantations were established in the 1960s and 1970s in some of the western sub-catchments, with up to 90% forest cover. Forest cover in other parts of the catchment is typically mixed coniferous and deciduous woodland, concentrated along field boundaries. Soils on steeper hillsides are typically freely draining brown soils overlying silty glacial till, rock head or weathered head deposits. Towards the base of the hillslopes the ground is typically wetter and soils comprise sequences of gleyed clays and peats on sub-angular head deposits or alluvial deposits closer to the river (Soil Survey of Scotland Staff, 1970).

Bedrock throughout most of the catchment is comprised of Silurian poorly permeable well-cemented, poorly sorted sandstone greywackes (Auton, 2011). Extensive glaciation during the last glacial maximum has affected the superficial geology and soil types (Ó Dochartaigh et al., 2019). The western part of the catchment has extensive, thick and poorly permeable glacial tills (often >5 m thick) (Aitken et al., 1984) but with some highly permeable glaciolacustrine sands and gravels in isolated areas (Figure 1). The centre of the catchment has extensive alluvial and head sand and gravel deposits (up to 20 m thick) overlying bedrock or glacial till.

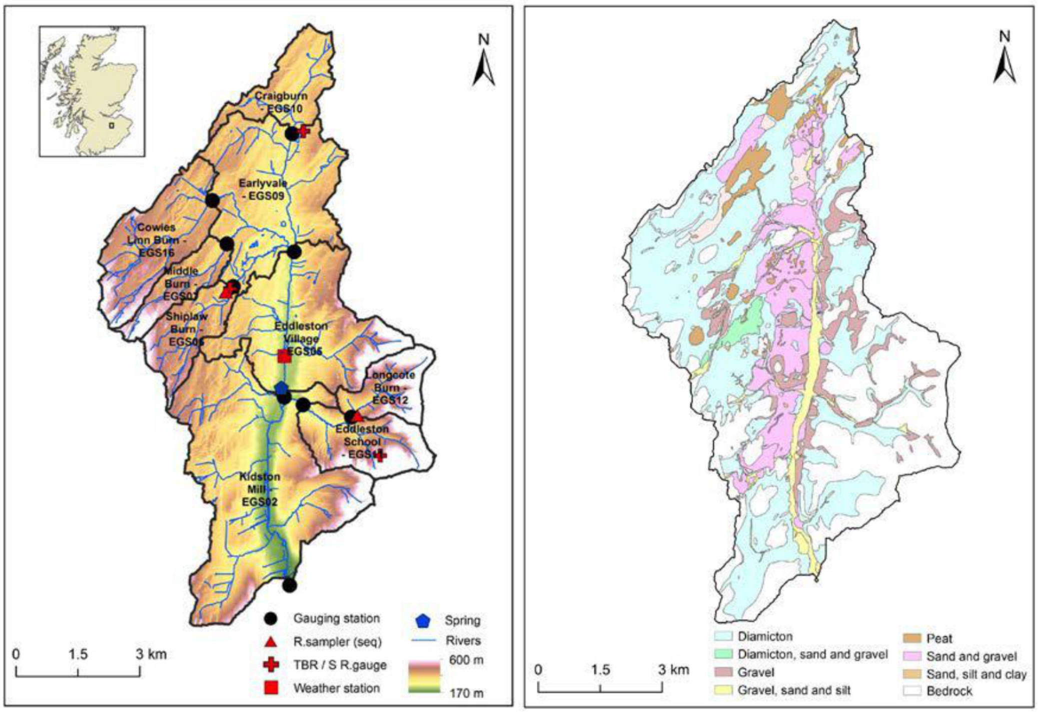


***Figure 3:** The Eddleston catchment: (left) topology and location of catchment within Scotland; and (right) superficial geology (Auton, 2011). BGS © UKRI*

## THE MODELS

In order to efficiently model the complex hydrology of the Cotswolds limestone, we developed a semi-distributed groundwater model. The aquifers were split into “buckets” representing groundwater subcatchments. The groundwater buckets receive recharge from a soil–water–vegetation model (SWAP, Kroes et al., 2017) as well as leakage from the river and produce baseflow to the rivers as well as lateral groundwater flow to neighbouring buckets. Direct run off produced by SWAP was routed to the subcatchment outlets with a cascade of two linear reservoirs (Moore, 2007). The model was calibrated against river flows for eight gauging stations (17–46 years’ data) using PEST (Doherty, 2005). The calibration process produced 47 “acceptable” model instances, defined as exceeding a certain threshold of Kling-Gupta efficiency (KGE) at each gauge. The model performs well, with acceptable models having KGEs of 0.75–0.92 at Eynsham.

In the Eddleston catchment, we implemented a more traditional hydrological model, DECIPHeR, a version of Dynamic TOPMODEL developed by the University of Bristol (Coxon et al. 2019). Originally developed by Beven and Freer (2001), Dynamic TOPMODEL has been applied in a wide range of studies, and has been shown to perform well in over 1000 UK catchments (Coxon et al. 2019). For the purposes of the study, we made two adjustments to DECIPHeR in order to better simulate different land uses. First, we incorporated the widely applied interception model of Rutter (e.g. Rutter et al., 1971) into the model, using the parameterisation of Dunn and Mackay (1995). Second, we modified the soil zone to explicitly account for soil and land use, using the method of Griffiths et al. (2006), which has been applied extensively to UK catchments. The model was run at an hourly time step for the period 2011–2021. The model was calibrated with a Monte Carlo approach comprising 162,000 runs. Performance was measured with the Nash-Sutcliffe efficiency (NSE) for the five largest peaks in the period 2014–2021 as well as monthly mean flows. 200 acceptable models were identified as exceeding an NSE of 0.8 at the outlet (Kidston Mill) for all five peaks and mean monthly flows.

## WOODLAND SCENARIOS

For the Thames at Eynsham, four woodland scenarios were developed: two broadscale planting scenarios that convert all grassland and arable land into either broadleaved or spruce woodland; and two refined scenarios that convert 78 $km^2$ (9% of land overlying the Cotswolds limestone). The refined scenarios were derived from discussions with local stakeholders, and considered an absolute maximum of what would be feasible and acceptable for broadleaved woodland in the landscape. The scenarios and the base case were run on a daily time step for the period 1971–2017.

For the Eddleston Water, four woodland scenarios were developed, all of which were broadscale. Two planting scenarios convert all grassland and upland into either broadleaved or coniferous woodland (broadscale); and two scenarios convert all upland and semi-natural grassland into coniferous or broadleaved woodland, i.e. excluding pasture. The scenarios and the base case were run on an hourly time step for the period 2011–2021, and the events used in the calibration were analysed.

## RESULTS

The effect of tree planting on peak flows at the Thames at Eynsham for various return periods is shown in Figure 4. The refined broadleaved and spruce woodland scenarios have only a limited impact on peak flows (0.2–2.6%), with the greatest effect seen with spruce woodland for peak flows with return periods of 1–2 years (Figure 4a). The two broadscale woodland scenarios have a greater effect on peak flows, although the effect of broadleaved woodland is still small relative to the scale of the intervention (1.7%–6.7% for broadleaved vs. 16.0%–24.7% for spruce woodland). All woodland scenarios lead to a drop in low flows, the largest of which is a 39% reduction in Q95 for the broadscale spruce scenario.

The effect of tree planting on peak flows in the Eddleston Water is shown in Figure 5. Relative to the scale of the intervention, impact is minimal for all peaks occurring in November and December (<1.7%). The impact is much greater for the peak occurring in October 2021 with reductions in the range 3.8–14%.

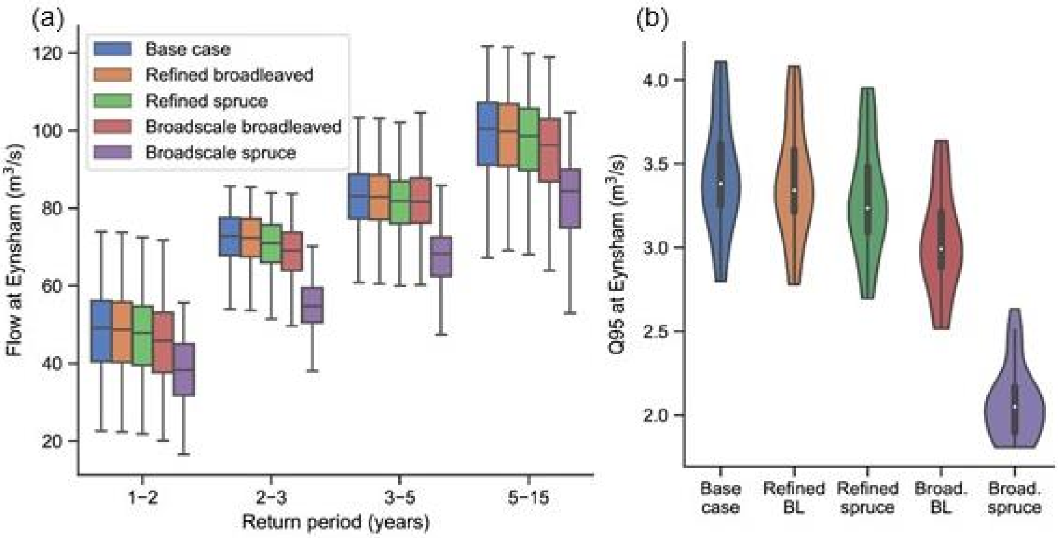


***Figure 4:*** *(a) Annual peak flows grouped into associated return periods for woodland planting scenarios. Ranges include several floods within the given return period interval as well as the uncertainty derived from the range of acceptable model results. (b) Q95 flow for woodland scenarios for all acceptable models. BL, broadleaved. From Collins et al. (2023)*

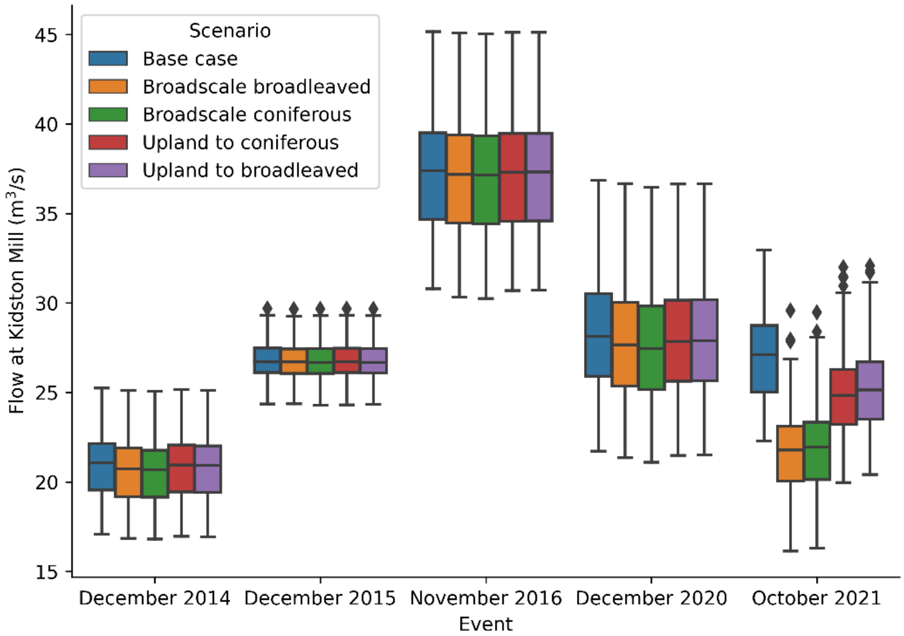


***Figure 5:*** *Flow at the outlet of the Eddleston catchment for five peak flows and woodland planting scenarios. Ranges include uncertainty derived from the range of acceptable model results. From Collins et al. (2023)*

## CONCLUSIONS

Woodland creation has a limited potential to reduce peak flows both in lowland permeable catchments and upland impermeable catchments. In our large lowland catchment, we find that only extreme levels of spruce woodland have a significant impact on peak flows, but that they also reduce summer low flows, potentially affecting water supply. In our impermeable catchment, extreme levels of woodland planting only have a significant impact on a peak flow occurring in autumn, suggesting woodland may be able to reduce flood risk in summer through autumn, but, by late autumn to early winter, the catchment has wetted up and the trees play a minimal role. The role of trees in NFM is likely to be restricted to small, impermeable catchments and convective summer storms or autumn frontal storms.

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# GROUNDWATER NBS TO BUFFER CLIMATE EXTREMES – INTRODUCTION TO THE WATER4ALL CLIM-EXPE PROJECT

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## ABSTRACT

*Mitigating the impact of extreme hydrological events and ensuring safe water supply for humanity and ecosystems is one of the greatest challenges of our time. The main water reserves are in the aquifers, as groundwater. The connection of groundwater to surface water bodies and ecosystems makes these reserves vulnerable to extreme events, but in this context, general knowledge of groundwater is very limited. Managed Aquifer Recharge (MAR) is an engineering approach to the intentional recharge of aquifers. The approach proposed by the group considers groundwater flow systems in MAR techniques providing a new nature-based MAR approach (NB-MAR) which can play a future role in the mitigation of extreme climate events. The research intends to display: 1) the influence of natural extremes on groundwater, 2) the application of NB-MAR to buffer climate events, 3) the impacts on groundwater quantity/quality, 4) the workflow for the involvement of the NB-MAR in society engagement, communication, education, 5) the consideration of groundwater flow systems and their replenishment with excess water in decision-making, 6) the integration of NB-MAR to water policies and develop a sustainable regulatory environment. These goals can improve water management, resilience, security and contribute to human rights.*


**Key words:** *climate extreme, groundwater systems, water resource management, managed aquifer recharge*

## INTRODUCTION

Hydroclimatic extreme events causing water shortage (drought) or surplus (flood) have a clear impact on the affected areas, population, economic activities, and production chains. Global warming and increased evapotranspiration contribute to more frequent and intense precipitation. The past three decades were among the most flood-rich periods in Europe (Blöschl et al. 2020). On the other hand, the frequency and severity of meteorological and hydrological droughts have also increased in most parts of Europe. Moreover, drought is the most significant category of 'natural disaster' at global level based on mortality and socio-economic impact relative to gross domestic product (GDP) per capita (UN Water, 2018). Minimizing these impacts and ensuring water supply for humanity and ecosystems is currently one of the most challenging societal issues also due to the increasing global population and water demand. However, these problems are not confined only to water management but also cause infrastructural, agricultural, ecological and social troubles. For instance, a shortage of food and water initiates migration and generates transboundary and related diplomatic issues.

One of the most important water reserves for the future can be found under the surface as **groundwater**. However, the connectedness of groundwater to surface water bodies (seas, lakes, rivers) and ecosystems, which is usually unknown or neglected, makes these reserves vulnerable to drought, flood and contamination. Therefore, these invisible resources became the focus of attention in 2022 due to the theme of UNESCO World Water Day: 'Making the invisible visible'. Nevertheless, the general public knowledge of groundwater is very limited and based mostly on oversimplified concepts. On the other hand, aquifer systems have huge storage capacity to mitigate the undesired effects of these extreme events.

To utilize this chance, **Managed Aquifer Recharge (MAR)** is an engineering approach to the intentional recharge of water to aquifers by wells, infiltration ponds, induced bank filtration, in-channel modifications, rainwater and run-off harvesting etc. for subsequent use or environmental benefit (NRMMC, EPHC, NHMRC 2009). MAR offers numerous benefits including underground water storage, natural treatment, replenishment of overexploited aquifers, and maintenance of groundwater-dependent ecosystems (GDEs). In the latter case

MAR can be considered as a **nature-based solution (NBS)** to conserve or rehabilitate natural ecosystems. Upscaling of NBS to reach their full and significant potential is a general problem and thought to be the most challenging issue to achieve the 2030 Agenda for Sustainable Development (UN Water, 2018). MAR techniques are also local scale solutions with similar upscaling challenges.

**ClimEX-PE**

The Water4All Partnership, co-funded by the European Union within the frame of the Horizon Europe programme, aims at enabling water security for all. Its goal is to boost systemic transformations and foster the matchmaking between problem owners and solution providers.

The Water4All Joint Transnational Call which opened in 2022 and was focused under the theme "*Management of water resources: resilience, adaptation & mitigation to hydroclimatic extreme events & management tools".* An international and multidisciplinary consortium led by prof. Judit Mádl-Szőnyi from Eötvös Loránd Universiteit (Hungary) was subsequently formed, and a proposal entitled "***Climate Extremes buffering through groundwater flow-based Managed Aquifer Recharge and Public Engagement (ClimEx-PE)***" was successful in being shortlisted for funding in late 2023.

This concept has not been considered earlier, nor the unavoidable interactions of MAR with natural groundwater flow systems have been adequately established yet. Although hydraulic gradients are often considered in flow modeling as driving force (Rahman et al. 2013, Missimer et al. 2017, Bahar et al. 2021), in most cases high hydraulic gradient and flow rate are considered disadvantageous (Dillon et al. 2009, Kazner et al. 2012), whilst the potential positive effects of groundwater flow have not been systematically investigated yet. Understanding of the significance of groundwater flow is also held back by the usually applied aquifer-based approaches (Mádl-Szőnyi et al. 2022), which do not consider groundwater dynamics, but only deal with their unconfined or confined character, thickness, chemistry and hydraulic parameters. Furthermore, the lack of general knowledge related to groundwater and especially to the operation of groundwater flow systems is a fundamental shortage in all levels of the world's societies. Figure 1 below illustrates the natural scientific concept of groundwater flow-based or NB-MAR solutions.

In addition, little is known about the social and economic aspects of MAR solutions and their geographical disparities, which basically define the public acceptance of MAR. In contrast with centralized surface storage, MAR is decentralized, thus allowing for the diversification of water source types used to augment recharge (e.g., urban stormwater, treated wastewater) and helping to build local resilience. This is exactly why NBS and MAR often require cooperation among multiple institutions and stakeholders, something that can be difficult to achieve. There is a lack of awareness, communication and knowledge at all levels, from communities to regional planners and national policy makers, of what NBS and MAR, or even groundwater can really offer (UN Water, 2018). On the other hand, the fear of risks associated with water quality decline by pollutants of the recharged water further enhances public resistance (Zheng et al. 2023). This situation is further complicated by the different legal interests and regulatory approaches (e.g., water management, agricultural and energy law), different competences (i.e., EU, national, municipal), multilevel governance gaps (e.g., policy, funding, capacity, information, objective gap), diverse legislations across countries, and various place-based needs (OECD 2015) which are concerned in groundwater issues and necessitate coherent and science/evidence-based solutions and decisions.

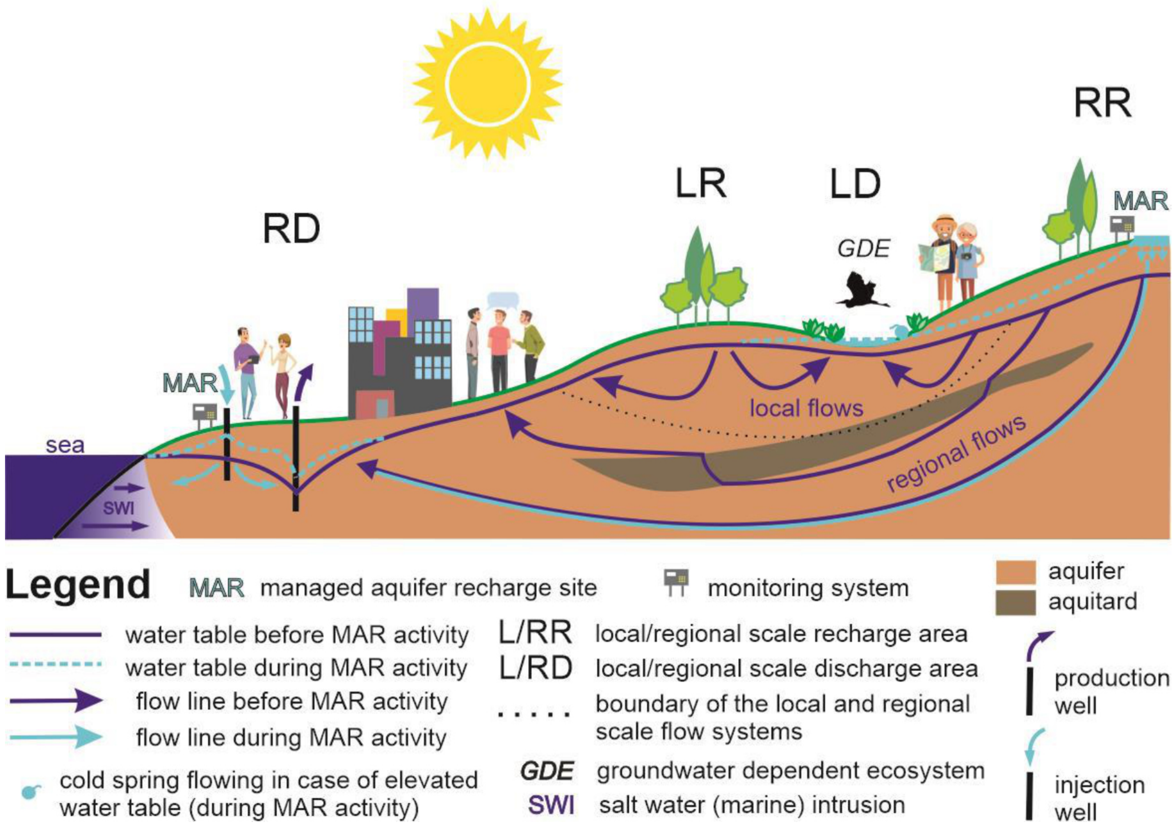


***Figure 1 Demonstration of the natural scientific concept of groundwater flow-based or NB-MAR solutions**. In the LD (local discharge) area: GDE rehabilitation by using an infiltration pond in the parent recharge area which also increases water table in the LD area. In the RD (regional discharge) area: salt water (marine) intrusion pushed back by an infiltration well and the water surplus arriving with regional flows from the MAR site in the RR (regional recharge) area.*

The **ClimEX-PE** project intends to cover all of these MAR-related issues through a strong consortium of five partners. This consortium includes four members of the **CHARM European University Alliance:** Eötvös Loránd University (ELTE, Hungary), University of Barcelona (UB, Spain), University of Utrecht (UU, Netherlands), and Trinity College Dublin (TCD, Ireland); whilst University of Zaragoza (UZ, Spain) joins as a self-funded partner. Trinity College Dublin are funded under the Water4All partnership by the Irish EPA.

## AIMS & OBJECTIVES

The main goal of the ClimEX-PE project is to incorporate groundwater flow system evaluation, local scale MAR techniques, and co-creative public engagement providing a new and upscaled nature-based MAR (NB-MAR) approach for regional scale mitigation of extreme hydroclimatic events.

**Specific objectives** of the **CLIM-EXPE** project are the followings:
● **Develop a generalized methodology to the application of NB-MAR approach** based on i) the basin scale evaluation of hydroclimatic extreme events and groundwater flow systems, and ii) the quantitative and qualitative assessment of the natural impacts of local scale MAR sites in the study areas.
● **Explore the social and economic impacts** of MAR solutions by defining socio-economic impact indicators.
● **Set up a Decision Support Tool** to aid in the selection of appropriate sites for and technology of NB-MAR based on the environmental, social and economic characteristics.

● **Improve national and international science/evidence-based public policy and decision-making** by policy briefs, guidelines, and recommendations also responding to place-based needs to enhance resilience and water security by helping manage “too much” and “too little” water in a sustainable, integrated and inclusive way.
● **Enhance public awareness and stakeholder perception** to groundwater, MAR and the newly proposed NB-MAR by co-creative stakeholder engagement; design of digital, customizable communicational and educational packages including value propositions and social marketing strategies; and setting up an information and awareness dashboard.
● **Help European countries and extend this knowledge worldwide to counteract the global issues arising from drought and flood** including migration, poverty and international

# SESSION III

# IRISH ALLUVIAL DEPOSITS: A SUSTAINABLE NEW WATER SOURCE?

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## ABSTRACT

*Projected growth in Ireland's population and economy will place increased stress on the country's water resources over the next 30 years. During the same period, conflicting pressures arising from climate change and the need to move to a more sustainable society will require water managers to meet increased demand in an environmentally friendly manner. Although larger projects, such as new pipelines, have received significant attention, addressing shortfalls in areas away from major infrastructural developments can prove technically challenging and expensive.*

*Alluvial deposits occur widely across Ireland, and although they have sometimes been used to meet localized demand (up to 7ML/day), they have been largely overlooked as water sources, despite the benefits they offer. Bank filtration, in which contaminants are removed from river water passing through the ground, is widely used across the world as a low cost treatment technology. Irish alluvium displays considerable potential for employing this nature-based solution as part of water supply strategies. Moreover, a countrywide review of borehole records reveals that thick sequences of glaciofluvial deposits underlie some alluvium, either as part of more extensive outwash sequences, or as buried tunnel valley deposits. The suspected high transmissivity of these composite sequences, coupled with greater storage capacity than fractured rock, suggest that these units may act as a valuable yet underdeveloped resource in many areas, for which water treatment costs may be considerably lower than equivalent surface water supplies.*

*On the other hand, abstraction from these sequences may impact on stream flow and thus the ecological status of water bodies. Generation of simple numerical models, using available hydrogeological parameters for Irish alluvial/glaciofluvial aquifers, has provided an insight into their capacity to meet both acute and chronic demand shortages. Results suggest that, if pumping rates are properly managed, there is capacity to draw water predominantly from storage, with little to no impact to stream flow in the short term. On the other hand, despite their ability to satisfy acute demand, key knowledge gaps remain. These include the confidence in which available storage data may be used, while further quantification of the potential impact of rejected recharge in replenishing depleted aquifers proves necessary. This information will prove critical for demonstrating whether use of localized alluvial/glaciofluvial sequences will have environmental impacts in helping meet Ireland's future water demand.*

## INTRODUCTION

Population growth, rising living standards and more intense economic activity over the past three decades have resulted in an increase in demand for potable water across Ireland, leading to localised water stress at certain times. Although these events have been acute and infrequent problems, sustained growth in demand, coupled with the prospect of land use changes, increased flooding and drier summers, suggests that conditions contributing to shortages will become increasingly common. Satisfying demand requires the development of new strategies to manage water resources. The challenge of meeting sustained projected growth in demand is further amplified by the need to comply with environmental quality targets and more stringent abstraction / drinking water quality regulations.

Although larger infrastructural developments such as pipelines have received significant attention for meeting projected demand along proposed routes, elsewhere this approach may prove technically challenging and financially prohibitive. Moreover, surface water treatment requires significant operational outlays for chemicals, energy and waste disposal. By contrast, more stable water raw water quality coupled with reduced infrastructural overheads makes the broader development of groundwater an attractive option.

Across Ireland, groundwater development to date has focused principally on productive bedrock aquifers, and on unconfined glaciofluvial sand and gravel deposits to a lesser degree. Elsewhere the occurrence of less productive units has suggested that sustained groundwater abstraction was not viable. However, this approach has largely neglected localised alluvial deposits encountered in the vicinity of rivers and streams (Figure 1). Despite their limited areal coverage, schemes involving alluvium can often prove highly productive, whereas purification by natural processes operating as induced recharge occurs through the subsurface assisting in reducing treatment costs, e.g. reducing microorganism content. The widespread use of these induced bank filtration schemes to meet potable water demand across the world provides testament to the benefits and efficiency of this approach.

This article describes the findings of the initial phase of an investigation, undertaken on behalf of Uisce Éireann, to evaluate the potential of Irish alluvial and associated glaciofluvial deposits to assist in meeting projected increases in potable water demand. This phase involved the review of available geological and hydrogeological data and accompanied by construction of generic numerical models aimed at reproducing essential features of the targeted field settings. These steps provided a preliminary assessment of the potential of alluvium and associated deposits to act as a nature-based solution to satisfy increased demand in an environmentally friendly manner that meets regulatory requirements.

## GEOLOGICAL SETTING AND HYDROGEOLOGICAL PROPERTIES

Localised use of alluvium across Ireland has focused largely on supplying water using infiltration galleries, in part because of assumed limited aquifer thickness. More recently, this assumption has been called into question as boreholes have revealed substantial thicknesses of unconsolidated glaciofluvial sands and gravels underlying floodplains in some river valleys. In many cases the valleys host 'misfit' rivers and streams which are significantly smaller than anticipated for the extensive sand and gravel sequences they host.

Further examination of composition, texture and geomorphological setting of these deposits suggests they are relict (paraglacial) deposits, laid down at the end of the last ice age, before deposition of Holocene alluvium under less energetic conditions. A review of Geological Survey Ireland (GSI) and Geological Survey of Northern Ireland (GSNI) well and borehole data from across the Island of Ireland has helped identify key areas where these composite Pleistocene glaciofluvial/Holocene alluvial sequences have been encountered, while evaluation of associated hydraulic data has provided information concerning their hydrogeological properties (Table 1).

Data presented in Table 1 summarise the variation in hydrogeological properties identified in glaciofluvial/alluvial deposits underlying Irish river valleys, while associated borehole data have shown some locations contain sequences in excess of 50 m thick. Moreover, borehole logs, lacking corresponding hydrogeological data suggest these deposits are more widespread and can reach thicknesses in excess of 100m. Figure 1 summarises promising locations where these sequences may occur. Critically, many occur in areas where significant growth in demand for potable water is anticipated over the next 20 years, yet water infrastructure remains to be further developed.

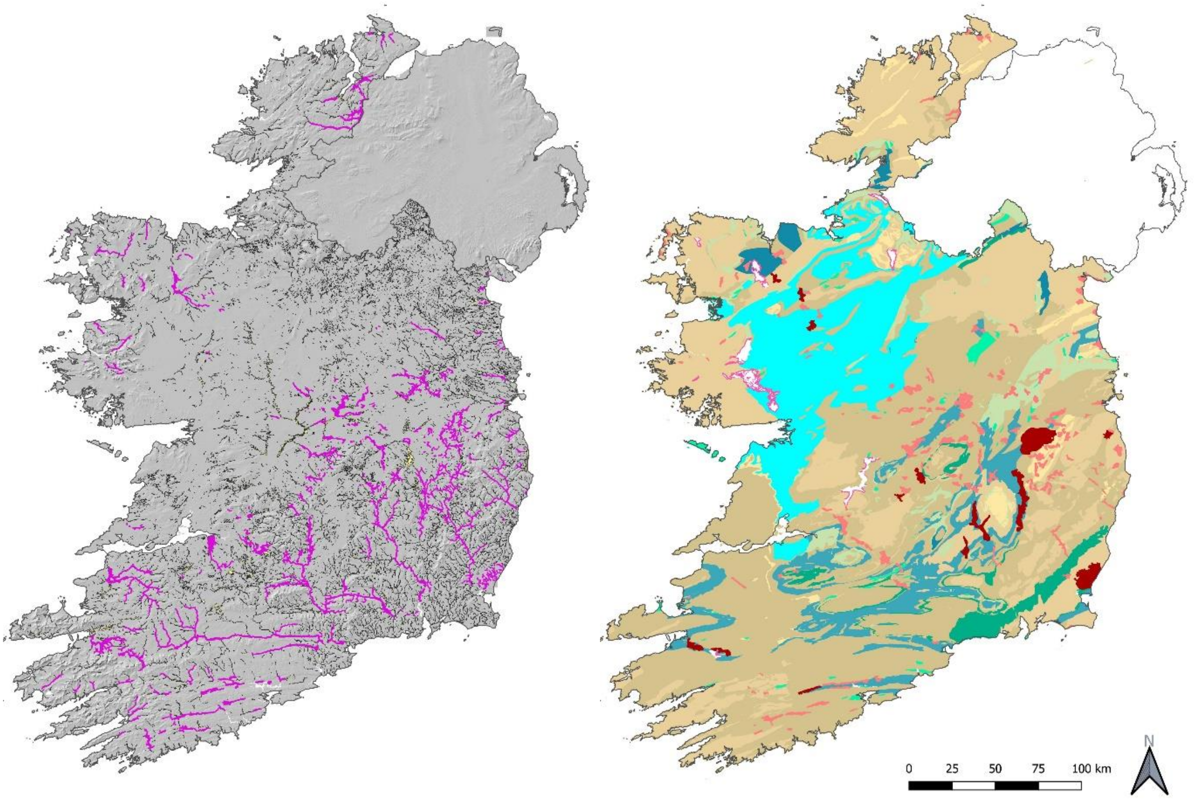



***Figure 1:*** *(Left) Map of Ireland showing the occurrence of alluvial deposits. Those shown in purple reflect areas with suspected sand and gravel sequences capable of providing significant quantities of water. (Right) Aquifer map of Ireland with brown areas indicating areas of low and moderate productivity aquifers. (Image: Geological Survey Ireland).*

## SOURCES OF WATER CONTRIBUTING TO DISCHARGE

Groundwater offers a potential supplemental source of water to help meet demand. Evaluation of the capacity of river valley deposits to do so in a sustainable manner, while not having adverse impacts on the ecology and legal status of adjacent water courses, poses key challenges around which the viability of water resource developments needs to be undertaken. Despite the relative novelty of this issue in Ireland, a significant body of research has been performed elsewhere across the world, leading to the development of key concepts surrounding the wider environmental impacts of groundwater abstraction in river valley settings. Quantifying these impacts in Ireland lies at the heart of this process.

Key to determining the impact of groundwater abstraction on river flow is identification of diverse sources of water contributing to well discharge. This includes induced bank filtration, drawing river water to pumping wells, while removing many substances present in river water through their interaction with aquifer materials. While a considerable body of research has demonstrated the ability of this approach to remove a wide range of contaminants and thereby reduce water treatment costs, indirect abstraction of significant amounts of river water can have negative repercussions on the flow volumes and water quality of aquatic ecosystems.

*1. **Table 1:** Summary of available aquifer properties data for aquifers comprised of alluvial and/or glaciofluvial deposits in the Republic of Ireland.*

| • Parameter | • n | • min | • median | • mean | • geometric mean | • max |
|---|---|---|---|---|---|---|
| • Transmissivity ($m^2/d$) | • 26 | • 22 | • 378 | • 670 | • 319 | • 3000 |
| • Storativity (-) | • 4 | • 2.7 x • $10^{-4}$ | • 1.7 x • $10^{-3}$ | • 2.1 x • $10^{-3}$ | • 1.2 x • $10^{-3}$ | • 4.5 x • $10^{-3}$ |
| • Specific capacity ($m^3/d/m$) | • 25 | • 22 | • 313 | • 622 | • 297 | • 4189 |
| • Hydraulic conductivity (horizontal) (m/d) | • 26 | • 1.25 | • 40 | • 70 | • 38 | • 478 |
| • Measured yield ($m^3/d$) | • 25 | • 4 | • 1500 | • 1275 | • 824 | • 3052 |
| • Specific yield (-) | • 5 | • 8.3 x • $10^{-3}$ | • 0.082 | • 0.083 | • 0.054 | • 0.2 |
| • Thickness of alluvial/glaciofluvial deposits (m) • (data derived from boreholes used for aquifer properties dataset above)[1] | • 27 | • 4.5 | • 15.5 | • 19.2 | • 15.7 | • 70 |
| • Thickness of subsoils within promising alluvial/glaciofluvial reaches (m) • (data derived from GSI wells/ geotechnical boreholes datasets)[2] | • 10,743 | • 0.1 | • 6.1 | • 7.9 | • 5.7 | • 93.6 |

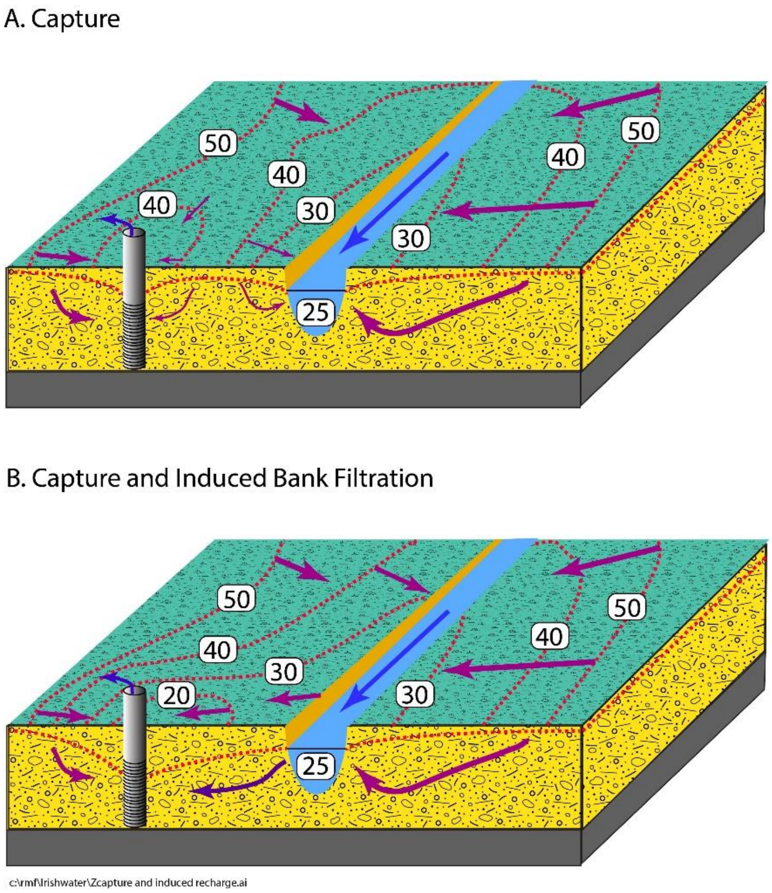
Critically, river bank filtration need not occur for groundwater abstraction to impact river/stream flow. Groundwater flowing toward a watercourse can be intercepted before it reaches surface water. Indeed, it is feasible to pump alluvial deposits, yet never pump river water (Figure 2A). Captured groundwater, coupled with induced river water (Figure 2B), is

*[1] Data include thicknesses of subsoils where drilling has not reached bedrock as well as where bedrock has been met; therefore, the different statistics calculated from the database may be undercalculated.*

*[2] As above, data include thicknesses of subsoils where drilling has not reached bedrock as well as where bedrock has been met. Furthermore, drilling records show different levels of quality, especially regarding subsoil logging, and may not accurately reflect the thickness of alluvial/glaciofluvial sequences.*

collectively referred to as "stream flow depletion". It is the only source of water contributing to well discharge under steady state conditions, leaving aside the possibility of transfer of groundwater from adjacent basins, including neighbouring bedrock aquifers ("boundary effects").

On the other hand, it is worth emphasizing that groundwater abstraction from aquifers hydraulically connected to rivers and streams may not significantly impact streamflow. During the initial stages of pumping, prior to the establishment of steady state conditions, aquifer storage release is typically the dominant source of well discharge. With time the storage component declines, and the contribution from streamflow depletion becomes dominant (Figure 3). The rate at which this occurs depends upon abstraction rates, aquifer properties, aquifer geometry and the hydraulic connectivity of an aquifer with a watercourse. It is necessary to quantify these relationships to confidently assess the impact on surface waters of proposed groundwater development programmes.



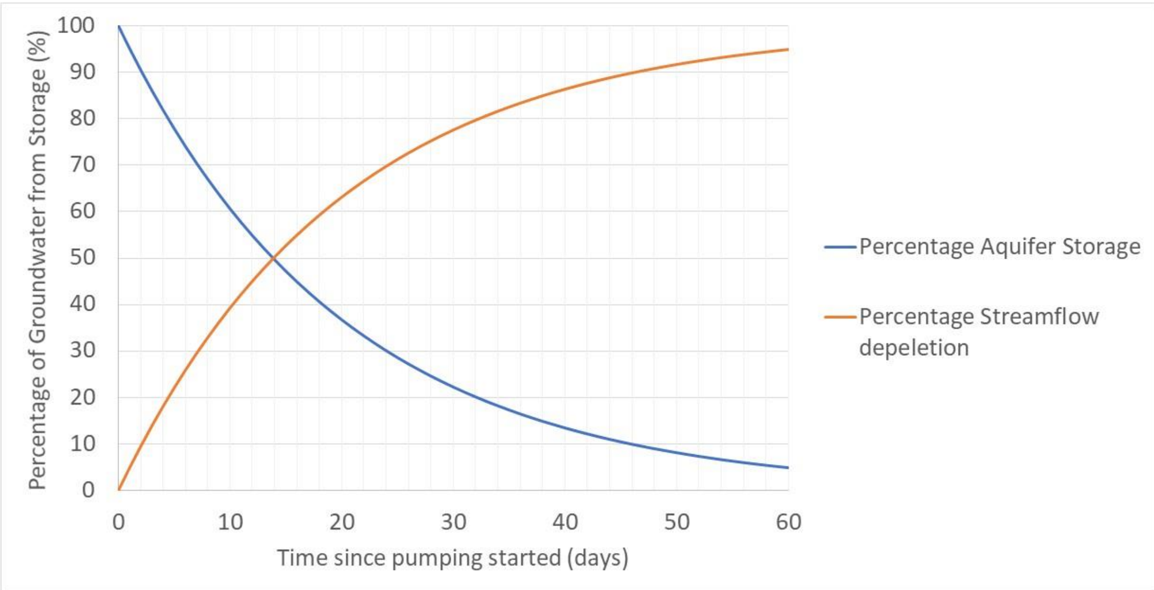

2. ***Figure 2:*** *Schematic representation of steady state contributions of induced bank filtration and capture to discharge from a well pumping an aquifer hydraulically connected to a river. Note that in some cases no water may derive from a river, yet capture continues to cause stream flow depletion.*

## MODELLING

Groundwater modelling provides a valuable means of quantifying hydrological impacts arising from development of alluvial / glaciofluvial (floodplain) sequences in Irish settings, while also highlighting key data needs and the utility of existing datasets. In the current project, the process is implemented in a stepwise manner, in which the availability of new data enhances the ability of the models to reproduce aquifer responses to pumping and predict the effects of development on future stream flow.

As a first step aimed at improving our understanding of the potential effects of pumping Irish river valley (alluvial and glaciofluvial) sequences on stream flow, a series of idealised analytical groundwater flow models provided a means for evaluating the relative influence of different factors on depletion. These factors include conventional aquifer parameters, such as T, $S_s$, and $S_y$, along with the influence of the degree of penetration of a river through alluvial deposits to the underlying glaciofluvial deposits. See Figure 4 for an example.

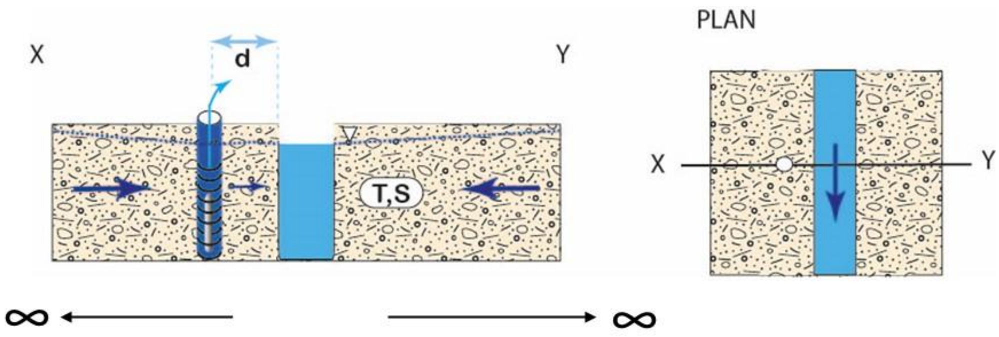
Although the idealised conditions, simulated using analytical solutions, provide an indication of the capacity of pumping to affect stream flow and the sensitivity of responses to aquifer parameters, the approach fails to account for more complex boundary conditions and variations in hydrogeological conditions encountered in Irish settings. Under these circumstances numerical modelling has proved necessary.

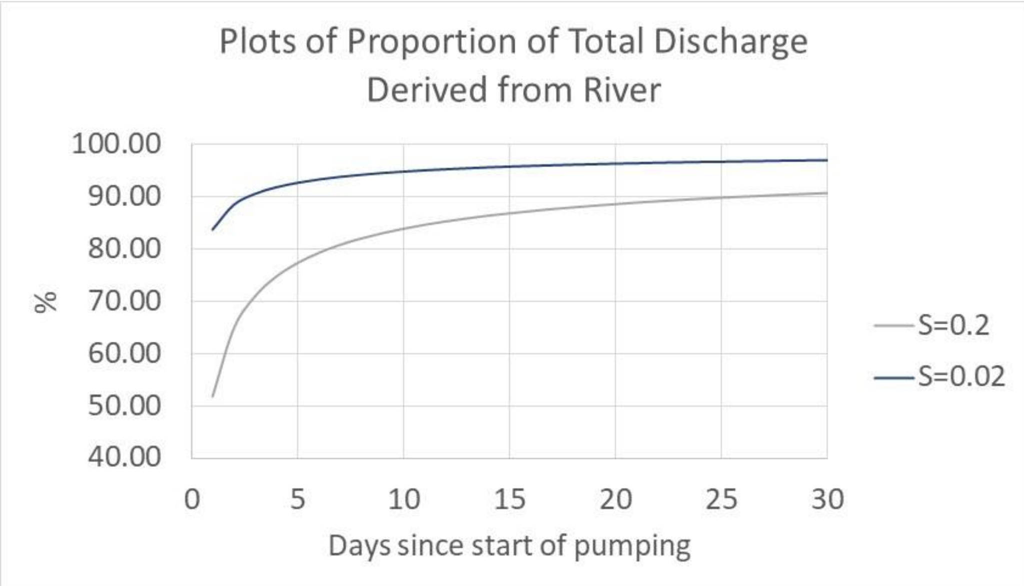



3. ***Figure 3:*** *Plot of change in contributions from aquifer storage and streamflow depletion with time. Once the proportion of water derived from storage drops below 50%, a system is considered depletion-dominated. Adopted from Barlow and Leake (2012).*

A second step in the analysis consisted of constructing four numerical (MODFLOW) models aimed at representing the range of expected geological conditions in the targeted settings (Figure 3). These consisted of:

4. Scenario 1a: 20m of glaciofluvial deposits, surrounded by impermeable bedrock and covered by 4m of less permeable Holocene alluvium. The river partially penetrates the alluvium and has a low permeability substrate. This setting corresponds to a semi-confined (leaky) aquifer condition in a narrow bedrock valley.
5. Scenario 1b: As above, but the alluvial deposits have the same hydrogeological properties as the glaciofluvial deposits, so that the setting consists of a single unconfined aquifer in a narrow bedrock valley.
6. Scenario 2: As Scenario 1, but the glaciofluvial deposits are surrounded by a regionally productive bedrock aquifer, corresponding to a narrow valley setting that is both vertically and laterally leaky.
7. Scenario 3: A spatially extensive sand and gravel aquifer locally overlain by 4m of alluvium. This setting represents a semi-confined condition for a wide bedrock valley.




*8. **Figure 4:** Output from the Glover & Balmer (1954) analytical solution reflecting influence of aquifer storage on the contributions to pumped discharge. The model assumes infinite aquifer extent and full hydraulic connectivity between the river and aquifer. Subsequent analytical simulations have demonstrated the sensitivity of the system to stream bed hydraulic conductivity and partial penetration of the shallower leaky (alluvial) layer by a river.*

The aquifer parameter values assigned the numerical models are representative estimates derived from the newly-assembled database. Recharge rates were considered constant over the duration of simulations.

Running the models under transient (unsteady state) conditions for the four scenarios allowed quantification of the sources of water contributing to pumping (at 1Ml/Day) under short term acute conditions (10 days pumping), seasonal conditions (10 day on/ 10 day off cycles over 100 days) and near permanent conditions (10 day on/off cycles over a two-year period).

## RESULTS

Glover & Balmer (1954) analytical model outputs highlighted the importance of reliable storage values for determining longer-term impacts on stream flow depletion, while outputs from more recent Hunt (2003) simulations demonstrated the need to quantify connectivity between the deeper aquifer and the river partially penetrating overlying alluvium. Table 2 summarises the results of numerical model simulations for all four scenarios.

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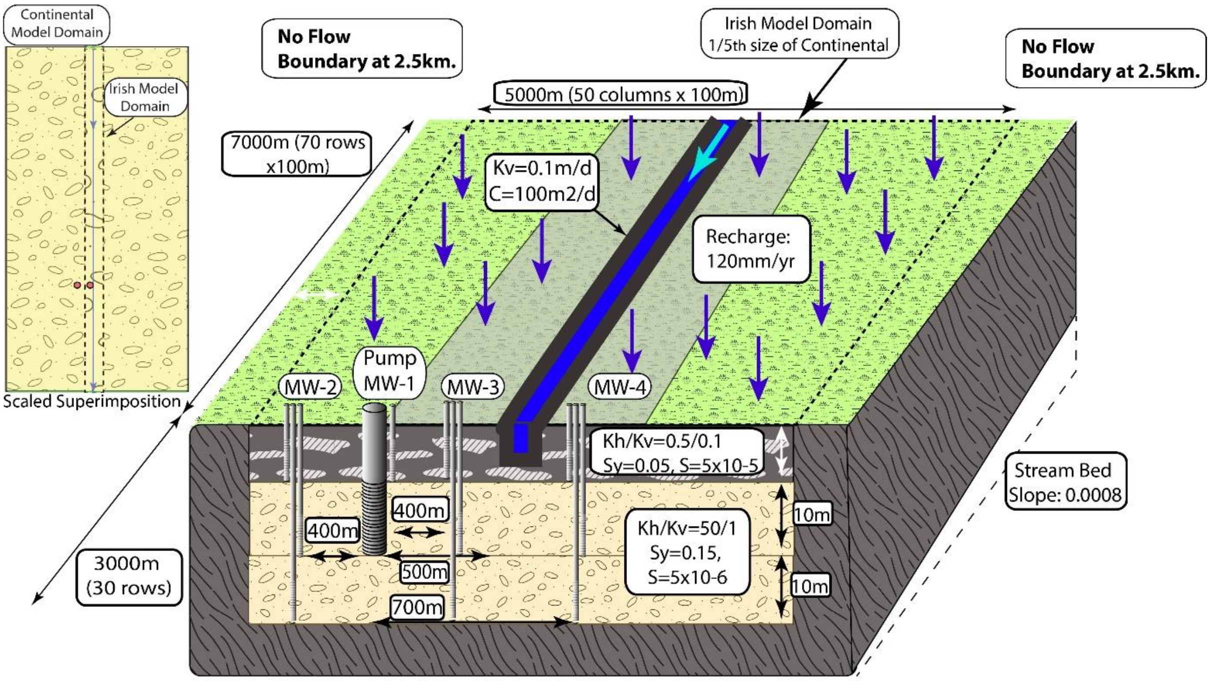


9. ***Figure 5:*** *Schematic summary of model configuration and variables for Scenario 3. The inset on the top left hand side reflects the relative dimensions of the smaller scale models employed in Scenario 1(a,b) and Scenario 2.*

Simulations show that storage dominates early time contributions in all scenarios, although this declines with time as streamflow depletion becomes more dominant. Nonetheless, after almost two years of pumping, storage continues to contribute almost 50% of pumped discharge. It should be noted that storage remains important because the simulated pumping is cyclically seasonal, giving the aquifer the chance to recover during unpumped periods. If pumping were simulated as continuous, the storage component would become very small more quickly.

Findings in Table 2 not only summarise water sources contributing to discharge, but also anticipated changes in groundwater levels. Critically, model outputs revealed that despite growing contributions from capture and induced bank filtration over the duration of simulations, hydraulic response parameters such as pumping well drawdown did not increase proportionately. On the other hand, outputs from Scenario 2 and Scenario 3 provide a useful insight into the capacity of adjacent (bedrock) groundwater units to affect stream flow depletion.

## DISCUSSION AND CONCLUSIONS

The results of the first phase of this investigation suggest that Pleistocene deposits underlying many Irish Holocene floodplains display significant potential to act as sources of additional abstractable water, which could help meet growth in demand. On the other hand, supply sustainability and quantification of stream flow depletion require more confident definition of aquifer parameters, aquifer geometry, and the relative importance of alluvial as opposed to glaciofluvial deposits.

A review of database aquifer properties has identified a significant number of localities where aquifer hydraulic conductivity/transmissivity has been determined. By contrast, localities where aquifer storage has been quantified are far fewer. Moreover, comparison of values determined by pumping tests are higher than those anticipated using geotechnical (aquifer compressibility) data (Domenico and Swartz, 1997).

*10.* ***Table 2:*** *Summary table of model outputs for three modelling scenarios highlighting the ability of aquifer storage to limit stream flow depletion.*

| Scenario | Time Since Start of Pumping (days) | Storage (%) | Induced** (%) | Captured** (%) | Boundary (%) | Pumping Well Drawdown (m) |
|---|---|---|---|---|---|---|
| 1a | 10 days | 86.3 | 1.2 | 12.5 | 0 | 1.31 |
| | 100 days* | 60.5 | 11.1 | 27.7 | 0.7 | 1.55 |
| | 720 days* | 46 | 18.5 | 33.8 | 1.6 | 1.63 |
| | | | | | | |
| 1b | 10 days | 87.1 | 2 | 10.6 | 0 | 0.91 |
| | 100 days* | 62.5 | 9.3 | 28.2 | 0 | 1.04 |
| | 720 days* | 46.3 | 16.6 | 36.8 | 0.3 | 1.09 |
| | | | | | | |
| 2 | 10 days | 80.6 | 2 | 11 | 6.4 | 0.96 |
| | 100 days* | 52.4 | 10 | 21.7 | 15.9 | 1.49 |
| | 720 days* | 44.1 | 13 | 24 | 18.9 | 1.53 |
| | | | | | | |
| 3 | 10 days | 95 | 0 | 5 | 0 | 1.02 |
| | 100 days* | 83.9 | 0.5 | 14.4 | 1.2 | 1.08 |
| | 720 days* | 54.4 | 2.7 | 32.9 | 9.9 | 1.14 |
| | | | | | | |
| | *Pumping for 10 days, followed by 10 days recovery.<br>** Collectively considered as stream flow depletion. | | | | | |

Evaluation of this discrepancy is suspected to arise due to complex aquifer geometry that results in significant deviations from conditions assumed in calculating storage terms using idealised pumping test analytical solutions, e.g. Cooper and Jacob (1946). Confident quantification of this term is necessary for determining the timing of a response that is storage-dominated to one that is depletion-dominated.

Model outputs, based on compiled aquifer parameters, suggest that in the case where pumping is seasonal, it may take a considerable period of time for a depletion-dominated state to occur, and that alluvial/glaciofluvial sequences may be able accommodate seasonal pumping to address acute shortfalls in supply. Moreover, it is noteworthy that international studies of streamflow depletion often derive from areas where abstracted water is required for irrigation, where a substantial proportion of abstracted water is lost to the atmosphere, thus leading to sustained loss of streamflow downstream of abstraction points, e.g. Burt et al (2002), Condon and Maxwell (2019). By contrast, if water is abstracted as potable supply, and then, after use, is returned downstream, the impacts to flow downstream of the return (wastewater) discharge point are considerably reduced.

Despite these benefits, it must be recognised that water withdrawn from storage must be replenished in some fashion for long-term sustainability. Investigations completed in the USA have shown that the impacts of storage depletion are routinely reported to take considerable periods (years to centuries) to recover in recharge limited systems (Barlow and Leake, 2012). By contrast, in areas where rejected recharge occurs, storage deficits may recover over shorter timeframes. Quantifying these issues will prove fundamental for assessing the potential for impacts to aquatic ecosystems due to groundwater abstractions, and will form a key investigative element of future phases of this project.

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# IRELAND'S LINKS GOLF COURSES - SUCCESSFUL PROVISION OF FRESH WATER IRRIGATION SUPPLIES FROM SANDS AND GRAVELS NEXT TO THE COAST
## Part 1

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## ABSTRACT

*Ireland has a quarter of the world's authentic Links golf courses. Over the past 12 years, hydrogeologists have successfully developed new fresh groundwater supplies for irrigation of Links golf courses on the coast of Ireland. This has enabled the courses to meet the international golf market's desire for all playing surfaces to be green, even during prolonged dry periods. High volumes of fresh water have been obtained by the careful exploration of the sand and gravel aquifers below each course. Many courses are fortunate that the sand and gravel aquifer lies above a layer of boulder clay. This prevents the upwelling of seawater from the open fractures in the bedrock below. The successful development of new water supplies requires appropriate siting and design of boreholes and wellfields. The boreholes are spaced out and pumped gently, hence 'spreading the load' on the groundwater system, and not creating a deep and extensive drawdown that will induce lateral saline water intrusion. The short grass and sand surface of a links course readily absorbs rainfall. Almost all rain effectively recharges the storage in the fine sand aquifer material. The large area of the courses means that the average rainfall recharge volume is a multiple of the amount of water abstracted for irrigation. In fact, some links courses receive too much recharge, and experience groundwater flooding.*


**Key words:** *Island, peninsula, groundwater supplies, coastal sand and gravel aquifers, Links Golf Course Irrigation*

## 1. INTRODUCTION

This paper focuses on the major findings from successful water supply development work on two important links golf courses near Dublin, over the last 12 years. These are Portmarnock Golf Club and The Royal Dublin Golf Club. Groundwater supply work in Ireland is usually concerned with exploiting water resources inland. Classic hydrogeology theory on saline intrusion, and salutary experience in different parts of the world makes hydrogeologists understandably wary of developing significant new water supplies along the coasts. The examples and findings in this paper are important because one links golf course is entirely surrounded by tidal seawater. The second is on a narrow peninsula with tidal seawater on three sides. Yet, in both cases it has been possible to develop sustainable, large volume water supplies for irrigation. A full discursive description of the work, the results and their interpretation over 12 years is not possible within the space constraints of a conference paper. Therefore, the paper consists of a series of paragraphs describing the main considerations and findings from the work. The objective of this paper, and Richard Langford's paper in these proceedings, is to provide information for our peers who, in the present and the future, may wish to consider the development of new water supplies, or the protection of existing water supplies along the coasts of Ireland.

Figure 1 Portmarnock Golf Club Course

## 2. THEORY

Fresh water is less dense than seawater. The Ghyben-Herzberg Theory or Ratio is taught in most hydrogeology training courses. It is easily understood, and it has a memorable name. It describes the theoretical relationship between a fresh water lens and saline groundwater under an island or along a coast. It was recognised by the two scientists in 1889 and 1901. The ratio is based on the relative specific gravity of fresh water and seawater. By this ratio, a lens of fresh water in an island that has a water table level 1 metre above sea level is expected to have a fresh water to salt water interface, in the sands below sea level, at 37metres depth. The less dense fresh water is, in effect, floating like an iceberg in the saline groundwater. Though the ratio is 1:37, it is often simplified to rough rule of thumb ratio of 1:40. Awareness of the ratio alerts the applied hydrogeologist to the probability that the salt-fresh water boundary will rise if pumping lowers the water level in the fresh water lens. For example, a sustained drawdown, of, say, 0.5metres would be expected to induce a rise in the interface of, 20metres. The threat of such a large change for such a small drawdown, understandably makes hydrogeologists wary of pumping fresh groundwater under an island or close to the coast.

Richard Langford and I were involved in the design, location and construction of boreholes and clusters of different depth observation holes in the beach at Magilligan's Point in 2016-2018 to provide the infrastructure for field research into saline intrusion, by Queen's University Belfast and Imperial College London. Their laboratory modelling predicted the Ghyben-Herzberg ratio relationship, with a tongue of saline water extending inland under the beach and fresh water flowing o

ut above it. However, the results, using the new infrastructure to monitor salinity at different depths, correlate with geophysics and pumping tests, showed that the upper part of the beach sands contain salt water. Below this is a tongue of fresh water with salt water below. The research showed that there is an intertidal circulation zone above the tongue of fresh water. It is important to recognise that the Ghyben-Hertzberg Ratio describes the theoretical static condition of a lens of fresh water in an isotropic porous media of infinite depth and width. It does not take into account the heterogeneity of natural materials, the effect of tides, recharge or pumping, The learning from our work is 'bear it in mind, but do not be deterred by this famous ratio.' Specific site geology and abundant recharge will often mean that pumping can be carried out close to the coast without inducing saline intrusion.

## 3. CHARACTERISTICS OF LINKS GOLF COURSES

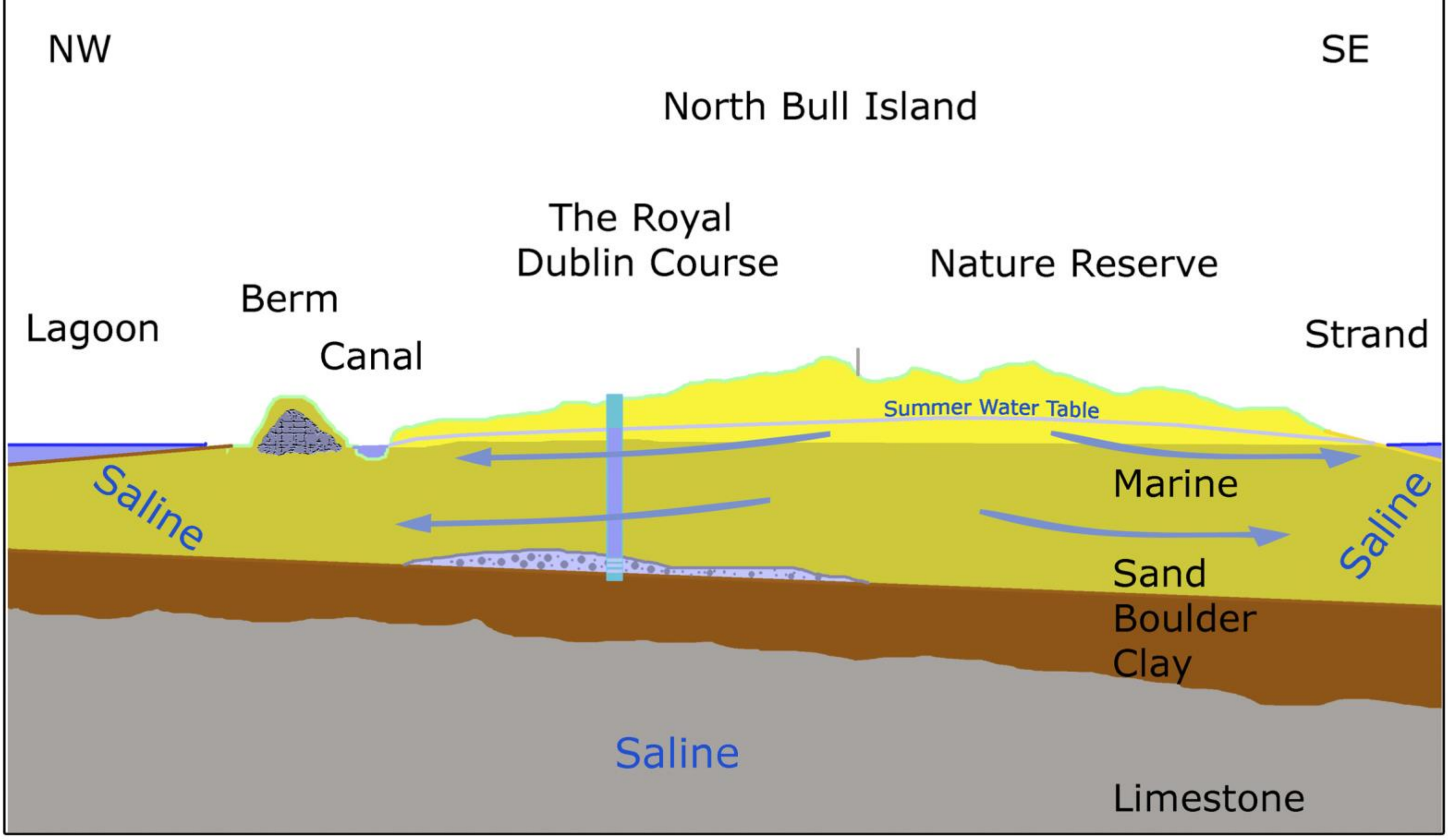
The design and maintenance of a links course presents many interesting hydrogeological considerations; some of which are favourable and others acutely negative. There are about 250 authentic Links Golf Courses in the world. Roughly 25% of them are in Ireland. An authentic links course (as defined by the Links Association) is 'a stretch of land near the coast, characterised by undulating terrain, often associated with dunes, infertile sandy soil and indigenous grasses which, when properly managed, produce the fine textured, tight turf for which links are famed.' Links courses are usually based on soft, loose windblown sand formed into gentle dunes. Yet, the preferred playing surface for the fairways on a links course should be hard, similar to concrete, so that when a driven golf ball lands, it bounces and runs on for a further 20 to 40 metres. To create a hard surface on soft sand means that the sand has to be held together by a mesh of grass roots, but to make it play fast ('long' in golfing terms), the grass also must be cut short. Repeated cutting leaves the grass scant leaf area for photosynthesis to create energy for growing roots. In addition, there should be little organic matter in the grass root zone that would retain water and nutrients, that, in turn, would make the playing surface soft and slow (short). In truth, the grass on the playing surface of a links course is stressed and barely kept alive. From a hydrogeological perspective the short

# Figure 2 The Royal Dublin Golf Course - North Bull Island


**Borehole Legend**

- 2inch piezos to 6m depth in the sands manually monitored since 2011
- 4inch exploration holes penetrating full thickness of sands Dec 2020
- 6inch exploration boreholes penetrating full thickness of sands (Feb 2022)

**Note:**
**Only Boreholes 3, 4 and 11 are pumped to provide water for irrigation**



grass on the playing surfaces, in conjunction with the coarse drought resistant marram grass in the rough, means that the transpiration losses and hence evapo-transpiration losses are small. It means that a large proportion of rainfall is effective in percolating into the ground and down to the water table. A classic, purist links course surface could be left to go brown during dry periods in summer. However, golfers prefer to play on green rather than brown grass, and letting the grass die in a drought would mean that the surface could become unstable and eroded by the wind and the passage of players. Ireland is fortunate in that rainfall can sustain the grass on links courses for much of the year, but to keep up with current trends, irrigation is often necessary to ease the water stress on the grass during the longer daylight hours and drying breezes in summer.

Links courses are favourites with golfers because they are usually playable throughout the year. Paradoxically, Ireland's rainfall works against this ideal. The water table under a links course is sometimes very close to the surface because the surface of the course is just above sea level. Drainage is sometimes necessary in low lying parts of a links course, in order to keep it playable during periods of heavy rain at any time of year, when rapid recharge into the groundwater system will raise the water table to the surface. Therefore, on the one hand the Links Managers want to keep as much fresh water below the course in groundwater storage for fear of the next drought, whereas the club members and visiting golfers want the course to be drained so that it is as dry as possible and 'plays long'.

Sustaining a world-class links course in Ireland requires the Links Managers to be acutely aware of a complex water balance, both for the grass and the water resources in the sand aquifer below the grass. The top Links Managers in Ireland are very receptive to experienced hydrogeological advice.

## 4. DESCRIPTION OF SITES AND GEOLOGY

The Portmarnock Golf Club was founded in 1893. The course occupies the middle and southern end of the Portmarnock peninsula. Roque's 1762 map of County Dublin, shows that the peninsula is approximately the same size and shape as the modern peninsula. Therefore, a peninsula of windblown sand dunes has existed above the high tide level for at least 250 years and probably a lot longer. This has given ample opportunity for rainfall recharge to flush out salt in the sediments and create a fresh water lens in and under the sand dunes.

***Figure 1*** *shows both an image of the course and the position of boreholes in wellfields. The figure also shows a schematic section across the peninsula in the middle of the course.*

Exploration drilling on this course in the 1990's and between 2013 and 2023, in the 1990s on the Hotel and Links Course to the north, and recent geophysics for the Greater Dublin Drainage Scheme long sea outfall. have shown that the sand above sea level is pale yellow-grey windblown sand containing abundant broken shell fragments. Below this there is up to 8 metres of fine, marine silty sand. The sands lie above a layer of boulder clay. The boulder clay is of variable thickness having been eroded by wave action before the silty sands were deposited. The bedrock is shown on GSI maps as either dark grey limestone and shale of the Malahide Formation, or calcareous mudstones and thin limestones of the Tober Colleen Formation. However, drilling in the south of the peninsula, and an outcrop on the Velvet Strand, just above the low spring tide level, shows that the bedrock below the south of the peninsula is the pale grey, karst weathered Waulsortian Limestone Formation. The sands lie directly on the Waulsortian limestone in the south of the peninsula. There is brackish water in both the dark grey limestones and the Waulsortian, but when a borehole into the bedrock is pumped the salinity rapidly rises.

The only opportunity to obtain a fresh water supply for the golf course was to develop the fresh groundwater resource in the fine silty sands, above the boulder clay in the middle and northern part of the course. It was important that each borehole penetrated the full thickness of the sands, and a short distance into the top of the boulder clay to prove its presence as a barrier between the fresh water in the sands and the saline water in the bedrock fractures and conduits. The highest dunes at Portmarnock are on the seaward side above the Velvet Strand. They are roughly 10 metres above Ordnance Datum. The lower parts of the course are about 3 metres above datum on the east side along the Baldoyle estuary. The groundwater level below the course at its highest in winter would be less than half a metre below the surface in the lower lying parts of the course.

The Royal Dublin Golf Club course occupies less than half the width of the south western end of the North Bull Island in Dublin Bay. Roque's map in 1762, does not show any island. Instead, the North Bull is shown as a sandy beach at low tide but completely inundated at high tide. In essence, 250 years ago, it used to look like the modern day Sandymount Strand. The first depiction of a nascent island above the high tide level is shown in a 1790's map of Dublin Bay. In the 1820s the North Bull Wall was built. This wall interrupted the anticlockwise circulation of sediment in Dublin Bay, and sand started to accumulate and become reworked by the wind, to form a small island against the north east side of the wall. By 1840 there were two islands. The larger island was 1.5km long. Eventually the two islands merged, and by 1885 a golf club had been created. By 1920, there was a very narrow version of the modern Bull Island. Bull Island continued to widen towards the southeast. The island roughly doubled in width between 1948 and the present day. It still appears to be increasing in width. There has always been an open tidal channel between the island and the Clontarf mainland throughout the growth of Bull Island. This channel or lagoon (sometimes called Raheny Lake) has been kept open by the discharge from the Naniken river and other streams flowing south into the bay.

***Figure 2** shows both an image of the course and the position of boreholes in wellfields. The figure also shows a schematic section across the island in the middle of the course.*

The old maps showing the evolution and growth of the island provide an important context for the study of the hydrogeology of the modern Bull Island. These maps show that the silty, fine sand sediments, now under the island, were deposited in a marine environment, and therefore will have contained salt water. This began to change when significant wind blown dune sand started to accumulate above the marine sediments after 1820, and a recharge mound of fresh rainwater could start to accumulate in the sands above sea level. There is now abundant fresh water in the marine deposits below the golf course. It has taken less than 200 years for rainfall recharge into the new island to push fresh water down into the marine sands, and effectively flush out the salt water in the pore spaces in the marine sediments. This has been most effective under the golf course area, which is on the oldest part of the island. The conductivity of the water under the centre of the course is around 1,100µS/cm$^2$. However, on the south eastern edge of the golf course, towards open sea, the sands are deeper and the conductivity is higher at the base of the aquifer, about 1,800µS/cm$^2$. It is important to recognise that as Bull island grows wider towards the open sea, the area receiving low salinity rainfall recharge is increasing. In effect the fresh groundwater resources of the island are increasing, and the process of fresh water flushing out the salt water is on-going, taking place on the south eastern side of the island.

The highest dunes are 6 metres above datum, which is lower than at Portmarnock. They form a series of low ridges down the spine of the island. The original land surface of the course on the north western side of the island used to slope gently into the marsh and the lagoon. There was no clearly defined edge to the course, and at high spring tides the sea would cross the marsh and invade the edge of the course. In 2002 and 2004 there were two storm-driven high spring tides that inundated a large part of the lower lying areas of the course. Ponds, at the time used as a source of irrigation water, were filled with seawater. The club thought that these ponds had become permanently saline and unusable. The Club built a long flood defence berm along the lagoon side and a similarly long collector drain on the inside of the berm.

Recent exploration drilling has revealed that the there is a thin bed of the fine-grained, relatively homogenous Dublin Port Clay below the marine sands. This overlies thick boulder clay, which in turn overlies limestone bedrock of the Lucan or Waulsortian Formations. There is no available information that indicates that the boulder clay has been eroded, as it has been under Portmarnock, and that the sands are in hydraulic continuity with the bedrock. All the evidence from drilling under the course shows that the original marine deposits below sea level are 6-8 metres thick with a continuous low permeability, clay layer at the base preventing the upward flow of saline water from the bedrock karst cavities and fractures.

## 5. PREVIOUS WATER SUPPLIES

Large scale irrigation at both courses is relatively recent. Up until the 1990s, it was just for the greens and tee boxes. At both Portmarnock and Royal Dublin water was taken from ponds forming water features on the course. These were dug into the sands and in essence they were like very wide diameter, very shallow, dug wells. There was little recognition that the water in these ponds was groundwater and not surface water runoff! In the 1980s and 1990s there was a move to irrigate the fairways, which required a much larger volume of water and new pipework, pumps, storage reservoirs and sprinklers. The ponds were not able to meet the new demand. The first development of groundwater consisted of three exploration bedrock boreholes at Portmarnock. These revealed the bedrock and the saline water within it. There was no attempt to find water in the bedrock at Royal Dublin because they were aware of the failure at Portmarnock. There was no attempt at either course to drill shallow water wells in the sands. Instead both courses employed civil engineering groundwork contractors and pump suppliers to install lines of well points close to new reservoir tanks in the centre of each course. The well point arrays lines numbered up to 100 individual 6metre long 2inch PVC pipes with a very short filter tip at the base. The top of the well point pipes were joined by a flexible hose to a collector suction pipe, that was sucked by a 15kW electric surface mounted centrifugal pump. Each club had two well point arrays and two pumps. The pumps exerted a suction force on all the well points equally. However, the yield characteristics of each well point varied. Some were more productive than others. Some well points had a high drawdown and often after a short period of pumping started to suck air. This broke the suction in the collector pipe, interrupted the suction on the other well points and the pump revs surged until the water flowed again. Over time the yield from the well points decreased because sand and ferrophyllic bacteria and manganese deposits clogged the filter tips. After 2010 both Clubs recognised that they were short of water during summer. With the pumps operating 24 hours a day, consuming 720 kWh of electricity, the yields fell dramatically after three days down to around 100-150 cubic metres per day ($m^3$/day). Portmarnock required about 500$m^3$/day but ideally wanted 600-800 $m^3$/day. Royal Dublin required 250$m^3$/day but ideally wanted 350$m^3$/day. They both tried supplementing the yield from the well points by again pumping ponds.

Pumping ponds may seem attractive, because at the start of pumping there appears to be a large volume of water in the pond. However, the rate of groundwater flow into a shallow pond is slow. This is because it is not possible to obtain sufficient drawdown in a shallow pond to create sufficient gradient between the level in the pond and the groundwater level in the sand aquifer around the pond, sufficient to overcome the resistance to flow through the fine sediments on the floor and sides of the pond. I did experiments at Royal Dublin on a very large 50cm deep pond with a powerful pump, extracting 250 $m^3$ of water in 30 minutes. The water level in the pond went down 5cm, but in the following 24 hours did not recover. I pumped the same volume on several successive days. The water level went down 18cms and it was only after a week when pumping had ceased, and there had been rain, that there appeared to be the start of a slow recovery in the pond water levels. Pumping water out of ponds that are water features reduces their visual attractiveness and their amenity for waterfowl during the nesting season.

Portmarnock Golf Club realised the limitations of the inefficient, expensive to operate, well points and the ponds before Royal Dublin, and engaged Richard Langford and myself to find and develop alternatives. The exploration and development programme began in 2013-14 and was very successful by the time of the drought in the early summer of 2018. During the drought Portmarnock was able to access to over 1,400 $m^3$/day. During this short drought, all other links courses on the eastern seaboard of Ireland had insufficient water for irrigation of the fairways. Most went brown and considerable areas of grass died. Portmarnock was the only links course with green fairways, tees and greens at the end of June 2018. Royal Dublin, was particularly badly affected by the short drought. It decided to follow the lead set by Portmarnock in August 2018.

## 6. RECENT DEVELOPMENT OF WELLFIELDS DRAWING WATER FROM THE SHALLOW SAND AND GRAVEL AQUIFERS

Richard Langford brought me into his project to assess the water supply and resources at Portmarnock in 2013. We carried out tests to find out whether the wellpoints could be re-habilitated. They cannot, because the narrow diameter and small filter tip prevents effective airlift surging to clean the filter section and improve the hydraulic efficiency. We then drilled a deep exploration borehole to confirm the geological succession of sands overlying boulder clay above limestone bedrock. We backfilled the bedrock section to prevent saline water upwelling to invade the shallow sand aquifer. We drilled several narrow diameter shallow boreholes along the line of one of the wellpoint arrays and demonstrated that four 4inch boreholes penetrating the full thickness of the sands with long screens pumped by small 1kw pumps could sustainably deliver more water than 100 wellpoints. The sand aquifer consists of an almost homogenous silt and fine sand aquifer material. There is a large storage of water in the aquifer, but its very fine grain size means that it is difficult for the water to flow through the small pores, and into a borehole. We realised that wider diameter boreholes with a large screen open area would improve the hydraulic efficiency of future boreholes. We recommended the construction of two wellfields on the central axis of the peninsula; one in the centre and the second in the north of the course in order to stay away from the coasts and the direct hydraulic link between the sand aquifer and the salt water in the bedrock in the south of the peninsula. We worked with Aidan Briody using the large Knebel 97 TBR rig to drill 12 inch Symmetrix holes lined with 10inch Boode PVC casing and standard screen with 5mm slots covered by 300µ geotextile sleeve. The design objective was to use the screen as a form of scaffolding to support the geotextile and create as much direct contact as possible with the fine sands. We were then able to develop a natural gravel/sand pack outside the geotextile. The design objective was to create water supply boreholes that could be ‘sipped gently’ with a modest drawdown. Each would provide a moderate yield of 4-6$m^3$/h or 100 to 150 $m^3$/day. Cumulatively, the 9 new 10” boreholes plus the 5 earlier 4” boreholes would be able to meet the new target of 800 $m^3$/day. It turned out that during the drought of 2018 they were pumped at 1,400 $m^3$/day over six weeks. The boreholes are maintained by the Links Manager, Gary Johnstone, using airlift surging when required. Many boreholes have Diver loggers to measure water levels. The data is used to set and adjust pumping rates to maintain a modest drawdown. There is an iron-manganese biofilm issue with some of the boreholes, but the great advantage of fully penetrating boreholes with a large open infiltration area, is that they can be maintained by the Club’s ground staff, whereas, well points cannot. Portmarnock are preparing to bid for a major international golf tournament and extend the area of irrigation to pathways and green roads around the course. Six more boreholes were installed as a part of this preparation in 2022. The early and most recent boreholes were drilled by Stephan Petersen using his light weight Knebel rig mounted on a Unimog that is able to move around the course without marking the ground.

The work at Royal Dublin benefitted from the experience at Portmarnock. After a desk study, an assessment of the wellpoints, and an assessment of demand, six 6”exploration boreholes were drilled by Stephan Petersen. Two were drilled next to the course boundary near the central long axis of the island to determine aquifer characteristics and the salinity of the groundwater. It was found that the water at depth in the sand was slightly more saline than water under the rest of the course. The second borehole was drilled through 5 metres of boulder clay and one metre into dark grey shaley bedrock. The hole below the sand aquifer was backfill with bentonite. The third hole was drilled next to Curley’s Yard (the service centre and workshops for the ground staff). The same succession was found of windblown sand above marine fine sands and silts but at the base was found a thin bed of shells and pebbles with gravel. A good yield was obtained and a fourth borehole to explore the lateral extent of these gravels was drilled 45 metres away. It too encountered a thin basal gravel layer. Though these two holes were for exploration purposes, it was realised that they had the potential to easily become production boreholes because they were close to a power supply from the Yard and close to the main pipeline from the wellpoints to the reservoir for the irrigation system. The two other exploration boreholes 5 and 6 were drilled at the far northern end of the course and in the south of the course. The northern borehole No.6 was drilled through 10 metres of boulder clay and though 17.5m deep did not reach bedrock. It too was backfilled with bentonite up to the base of the sands. This borehole is unlikely to be used by the Club, and has been offered to the Geological Survey of Ireland as monitoring borehole.

Boreholes 3 and 4 were extensively tested, and with their 1.5 kW Grundfos pumps were found to be capable of replacing the 100 wellpoints and their 15kW pumps. The two narrow diameter exploration/production boreholes have been pumped for the past 4 years at up to 360 $m^3$/day at 10% of the cost of the well point pumps.

Royal Dublin are considering increasing the area irrigated with a new irrigation system that will require an increased abstraction rate. In 2022 there was a second exploration programme to find out whether the basal gravels extended to the southwest of Curley’s Yard. Two boreholes encountered a two metre thick layer of coarse gravel and pebbles at the bottom of the silty sands. A yield of 43 $m^3$/h, or over a million litres per day can be obtained from each borehole individually. However, an old, 800 metre long, 3inch rough pipeline to the reservoir will not accommodate such a flow, and therefore this high yield remains a potential.

The problem with an aquifer made up of marine silts and fine sands is that though they contain a lot of water they have a relatively low permeability. However, a very permeable gravel layer below these sands can be made to behave like a basal drainage blanket or layer. A borehole drawing water out of the gravels alone induces a downward pressure gradient in the overlying fine sands. The horizontal infiltration area on the contact between the gravel layer and the overlying sands, is a much larger area than can be created around the circumference of a vertical borehole screen. Tapping into the gravels alone indirectly provides much better access to the water stored in the sands above. It is an almost perfect combination aquifer; a high permeability drainage layer below a high storage layer means that the drawdown in the gravel layer does not need to extend far from the pumping borehole in order to be able to draw sufficient water from storage in the fine sands above. Pumping a large quantity of water from the storage only in the thin gravel layer, would create a very extensive ‘cone of drawdown’ in the gravels, that might extend out as far as a connection to the saline water at the coast. The release of water from storage in the overlying sands limits the extension of the drawdown.

## 7. RECHARGE, WATER RESOURCES, WATER DEMAND AND OPERATION OF BOREHOLES

The fresh water resources of both links courses is primarily determined by the effective rainfall recharge directly through the surface of the course and the volume of fresh water in storage in the shallow sand aquifer. The GSI has calculated the average annual effective rainfall. There is no recharge cap related to the bedrock aquifer classification because the recharge is into the sand aquifer above the bedrock. The effective rainfall for Portmarnock is 269mm/year. The area of the peninsula owned by the club is 120 hectares. Therefore, the average annual volume of recharge is 323,000 cubic metres of water per year. Taking conservative values for the saturated thickness (6 metres) and porosity/specific yield (20%) of the fine sand aquifer under the course, the estimated volume of fresh water in storage would be about 1,440,000 cubic metres. The golf course has its own automatic weather station. Irrigation usually takes place at night to reduce evapo-transpiration losses and because the course is in use during the daylight hours. The demand for water for irrigation varies in relation to the seasons, the antecedent and forecast rainfall, the wind speed, the air temperatures and the objectives of the Links Manager. Assuming that the irrigation system is used 100 days in the year and a high average volume of 800 cubic metres of water is applied each night, then the annual water demand is 80,000 cubic metres; this is less than 25% of the average annual rainfall recharge. In other words, 75% of the rainfall reaching the aquifer flows out to the coast.

The boreholes are pumped gently. There are three well fields. The objective is to ‘spread the load’ and not pump a lot of water from one area. A typical borehole would be pumped at about 4-6 $m^3$/h for about 12 hours. Each block of boreholes forming a wellfield can be turned on or off at a central control panel. The boreholes pump into a 1,000 cubic metre reservoir. Portmarnock has very little surface drainage. The course seldom floods during heavy rain. However, there are two low-lying areas where the winter water table is often very close to the surface. The Links Manager has occasionally turned on the conveniently located boreholes in one area to successfully lower the water table and keep the course in good condition for the players. The Links Manager sees the groundwater infrastructure as just one of his tools for managing the course. Knowing that he has a groundwater infrastructure that can give him more water than he needs, and knowing that he has more recharge than he can use, removes what had been a chronic anxiety before 2013. Knowing that the water resources are available and sustainable, gives the Club the confidence to invest and start negotiations to hold a major tournament.

The same calculations with similar values and assumptions can be made for Royal Dublin, except that the width of the course is less than half the width of the island and the groundwater catchment divide is probably below the ridges of higher dunes on the seaward side of the course boundary. The groundwater recharge catchment area is larger than the area of the course. The area of the course alone is 700,000 square metres. The effective rainfall is 252mm/y. Therefore, the volume of recharge is 176,000 cubic metres. The thickness of the saturated fine sand aquifer is roughly 6metres. Therefore the estimated volume of water in storage below the course would be 840,000 cubic metres. Royal Dublin requires less water for irrigation in part because the water table is closer to the roots of the grass in low-lying areas. Royal Dublin is currently using a maximum of 360 cubic metres per day. Over 100 days, it would use 36,000 cubic metres of water a year or 20% of the rainfall recharge not including the recharge flowing under the course from outside the course boundary.

In fact, Royal Dublin has a problem of too much fresh water, and drainage was a major consideration for the current Links Manager, Alan Hammond and his predecessor Paddy Teeling. In 2011 two pumps were put into a stilling well chamber on the collector canal on the inside of the flood defence berm. They were set with float switches that activated the pumps when the level in the canal was at a certain level. Unfortunately, this level was lower than the spring high tide level on the other side of the berm. The pumps were left on automatic for over 7 years, and they kept the level in the canal low throughout the seasons. The water was pumped from the canal out into the salt marsh at a rate of 36cubic metres an hour. There is a good record of the duration of the pumping time for each year. This gives an average of 12.8 hours a day. Using these data it appears that the pumps were discharging about 300,000 cubic metres of water a year into the salt marsh. This was more than the average recharge volume for the course lands. The water pumped from the canal was not all fresh groundwater. Keeping the level in the canal low, lead to salt water percolating under the flood defence berm and the conductivity of the water in the canal varied from 17,000 to 32,000µS/cm. The pumps on the canal were turned off in 2019, as soon as the impact was understood. A drop board sluice weir is soon to be installed to give the Links Manager control over the flow of water from the canal. Meanwhile, Arups briefly installed Divers that discovered a pulse of salt water makes its way under the berm into the canal on the highest spring tide.

Three exploration boreholes are in production at Royal Dublin. They pump into a small 250 cubic metre reservoir. The boreholes start pumping when the irrigation system switches on in the evening. The three boreholes are pumped at a combined rate of about 25m$^3$/h. The storage in the reservoir plus the water pumped into the reservoir during the 8-10 hour irrigation period enables the Club to apply 360-400 cubic metres of water each night. The boreholes carry on pumping during the day in order to replenish the level in the reservoir before the irrigation the following night. Pumping is not continuous. Usually, there is a 10-12 hour period for the recovery of water levels. The boreholes are roughly 150 metres from the saline water in the canal and 170 metres from the spring high tide level in the salt marsh outside the berm. There has been no increase in salinity in the water pumped from the boreholes, which remains around 1,100µS/cm.

## 8. BOREHOLE DESIGN AND WELL SCREENS

The findings during the work to obtain a water supply from marine and windblown fine sands and thin gravels, has largely confirmed previous experience on alluvial and coastal aquifers elsewhere in Ireland and overseas. It has emphasised the need to seriously think about the interface between the borehole and the aquifer, when designing the construction of a borehole, and how to make it easier for water to get through the loose fine aquifer material, and then flow into the borehole void. It is too large a subject for this paper, but for brevity, I have found that the optimum design for a 6 metre thick relatively isotropic fine sand aquifer is a 5mm slot width, continuous slot screen supporting a double layer 300 micron geotextile sleeve. The same slot width continuous slot screen without the geotextile also gives excellent hydraulic efficiency and yields of over 40m$^3$/h from a 1metre thick coarse basal gravel layer.

## 9. THE IMPORTANCE OF WATER SOURCE AND RESOURCE MANAGEMENT AND TRAINING

The Links Managers for both links golf courses are acutely aware of the importance of their new water supplies and the need to monitor, interpret, understand and manage their groundwater resources, because they are both surrounded by sea water. One manager, goes so far as to smile every time it rains because he likens the rain recharging his sand aquifer, to someone putting money in his bank account. He knows that he may not need the water at the time, but that it will be there 'in the bank account' storage in the sand aquifer, for when he needs it during a hot dry spell in summer. Both Links Managers have been on site throughout and provided physical assistance during the drilling, airlift development, pumping tests and commissioning work. They have also brought their greens staff to the sites to observe the work. Recently, I have delivered a three hour long training workshop on hydrogeology and groundwater development and protection to all the ground staff at one

Club. The staff at both Clubs can now carry out airlift development on their boreholes without the need for advice, or supervision from a hydrogeologist. The respective Links Managers are enthusiastic about hydrogeology training, and they have willingly allowed post-graduate students from Trinity College, drillers on the Carlow training course and hydrogeologists from GSI to get field experience with drilling, airlift development and pumping tests.

## 10. CONCLUSION

The work on Links golf courses on a peninsula and an island has shown that significant fresh water supplies can be obtained and sustained. This is due to the large volume of effective rainfall recharge through the wind blown sands at the surface, and the presence of a protective low permeability boulder clay at the base of the shallow sand aquifers. The recharge on Bull Island has been remarkably effective at flushing the connate salt water out of the marine sands and silts in less than two centuries. The clays below the sand aquifer prevent the up-welling of salt water from the bedrock groundwater system. Sipping gently from numerous boreholes or wellfields, some located as close as 175 metres from sea, has cumulatively provided over one million litres of fresh water each day during a drought period, without inducing lateral saline intrusion. This can be done because the fine grained marine sands under the golf courses hold a large volume of water in storage. High yields from individual boreholes can be sustained if the borehole encounters a 1-2metre thick coarse gravel below the storage in the fine sands. The gravels act as a high permeability drainage blanket, and in essence the borehole becomes a collector well. Pumping groundwater from shallow ponds or partially penetrating well points is an inefficient and uneconomic short term method of drawing upon groundwater from a fine sand aquifer.

# IRELAND'S LINKS GOLF COURSES - SUCCESSFUL PROVISION OF FRESH WATER IRRIGATION SUPPLIES FROM SANDS AND GRAVELS NEXT TO THE COAST

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## ABSTRACT

*Irish golf links courses generally source water for irrigation from groundwater, surface water, a mains supply and/or a combination of all three. The cost of mains water makes that option prohibitive, while surface water is vulnerable to pollution upstream of the course. Therefore, groundwater is the most secure option for links courses. In the past, it was normal for golf courses to only water greens. In recent years, golf course irrigation system upgrades allow for fairway, tee box, and grass pathway irrigation, with a resultant increase in peak water demand. Golf Link Courses do not tend to use large volumes of water daily; rather they require the capacity to apply large volumes in the event of an extended dry period and after applying surface treatment, or turf repair. Irrigation water is usually applied at night, minimising evaporation losses and maximising the return of excess irrigation water to the underlying aquifer. This paper outlines three case studies of groundwater supply development projects from three locations around the coast of Ireland where groundwater abstraction takes place within close proximity to the coast.*

**Key words:** *Ballybunion, County Louth, Royal County Down, Sand and Gravel Aquifer, Golf Links Irrigation.*


***Figure 1**: Golf course locations*

## BALLYBUNION GOLF CLUB CASE STUDY

Ballybunion Golf Club comprises both the “Old Course” and the Cashen Course, and occupies an area of approximately 112 hectares. The golf club is situated on sand hills, which extend from Ballybunion village in the north, to the mouth of the Cashen River, approximately 2.8km to the south-southwest. The sand hills slope steeply to Ballybunion beach along the western boundary of the golf course, and at the beach front appear to be underlain by rounded beach cobbles. The golf course is between 400 and 500m wide, and is surrounded by salt water of the Atlantic Ocean to the west, and brackish water from the Cashen Estuary to the south.

The golf club comprises two 18 hole links courses, The Old Course, and the Cashen Course. Parkmore Environmental Services Ltd was approached to assist in developing additional groundwater sources for irrigation in 2016 in advance of the installation of a new irrigation system on the Old Course.

Irrigation water was sourced from a combination of one shallow (15m deep) groundwater well, and one small stream which crossed the course. The groundwater well was pumped on demand to a storage reservoir. The water demand at Ballybunion is c. 40m$^3$/hour. The existing arrangement left a significant shortfall during dry weather.

Previously, three deep groundwater wells (134m deep) had been drilled on the course in 2011. Steel casing was driven into the top of solid bedrock to a depth of c. 20m BGL. The steel casing was perforated in one of the wells. Two of the wells were barren (no water), a third well drilled on the driving range provided very silty groundwater, which entered the well through perforations in the steel casing. No water entered the well through the bedrock.

Two wells, which had reportedly been drilled to c. 40m BGL in the 1970s had been abandoned due to the pumping of salt water. A 30m deep well was not in use.

Iron clogging of irrigation pipe work and sprinkler heads was a big issue for Ballybunion Golf Club. Iron deposits were present in the well head, on the pump, and the pump riser pipe was almost clogged with iron deposits.

## DESK STUDY, PRELIMINARY INVESTIGATION AND CONCEPTUAL SITE MODEL

A desk study review of available information completed in 2016 (consisting of Geological Survey of Ireland online maps and 2011 drillers logs) indicated the site was underlain by windblown sands, overlying pale grey lime rich mudstone of the Waulsortian Formation. The windblown sands were not classified as an aquifer by the GSI; the Waulsortian Limestones are classified as a locally Important bedrock aquifer (LI) indicating possible well yields of between 100 and 400m$^3$/day.

Test pumping of the active groundwater well was only possible after removal and replacement of the existing pump and gate valve (which had been corroded and clogged with iron). The shallow, 15m deep well, was capable of providing up to 25 m$^3$/hour with a drawdown of 4m. A second, 30m deep well, could provide up to 13 m$^3$/hour with 1m drawdown. However, the salinity of the water increased from 900 µS/cm to 1920 µS/cm after a few hours of pumping.

***Plate 1:** Iron Biofouling of BH101's Well Head*

***Plate 2:** Iron Biofouling Clogging Pump Intake at BH101*

The initial conceptual model was that a lens of fresh groundwater was available within the sand and gravel strata beneath the sand hills, and within some of the bedrock beneath the course. Groundwater is recharged by rain falling directly on the course, and by water moving through the sands, gravel and bedrock from the surrounding lands (Figure 2).

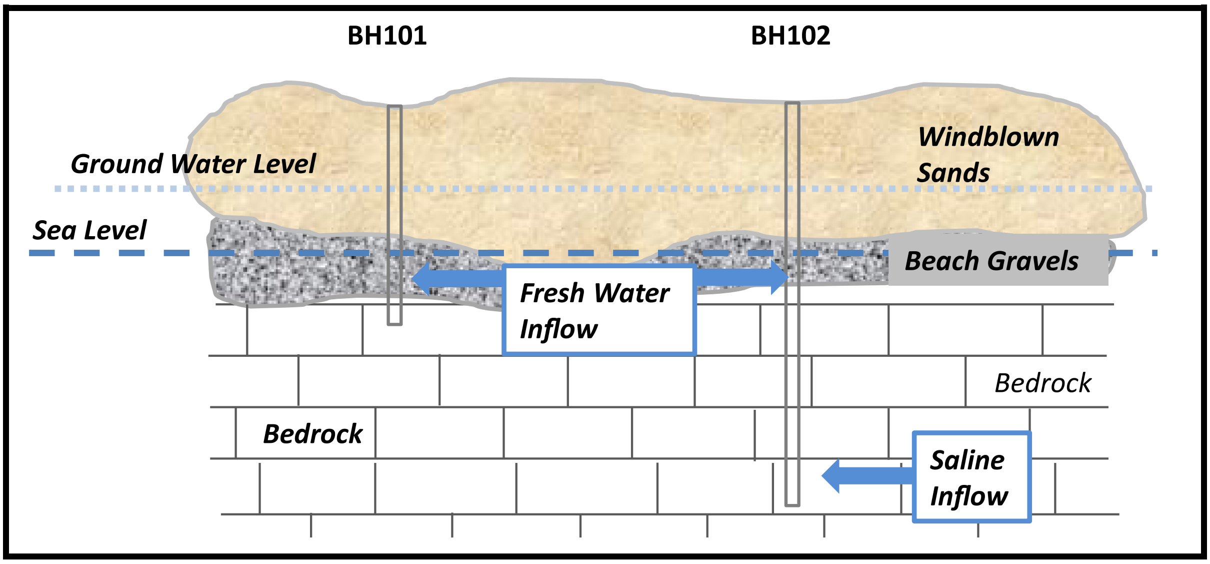


***Figure 2:** Initial Conceptual Site Model*

## GEOPHYSICAL SURVEY

A geophysical survey was conducted at Ballybunion to help identify possible locations for drilling. The aim of the survey was to establish depth to bedrock, delineate any structures within the bedrock which could transmit water, and identify any areas where salt water had invaded the underlying aquifer. The geophysical surveys consisted of 9 2D Electrical Resistivity Tomography (ERT) lines which were chosen to give a good spatial spread across the golf course within 3 days (Figure 3).

The geophysical survey results consistently indicate the presence of sand and/or gravel, or silt clay overburden to a depth of 15 to 20m below ground level beneath the course, overlying bedrock.

It appeared from examination of the geophysical survey sections that similar ground conditions found at BH101 could extend beneath the course to the north and south, and to the west towards the coast. These results were very encouraging in terms of the potential of developing a freshwater groundwater supply for the course; however, geophysical signals can be interpreted in many ways. Therefore locations required investigation by borehole drilling to confirm the ground conditions and groundwater potential.

## EXPLORATION WELL DRILLING

Given that the existing shallow 15m deep well successfully abstracts fresh water at the course, it was decided to target groundwater in the shallow aquifer, which was thought to consist of sand and gravel. Exploration boreholes were located reasonably convenient to the existing water supply infrastructure to reduce the burden in piping and running electrical supplies to future production well heads. Exploration drilling results were not as positive as expected. Only 3 out of 6 exploration holes provided a viable supply. No sand and gravel was encountered; rather the over burden consisted of low permeability boulder clay. Groundwater was sourced from the top of weathered bedrock, with yields of between 4 and 7m$^3$/hour achievable from three of the wells. The conceptual model was slightly off (it had been considered that groundwater could have been abstracted from weathered rock, however, it had been believed that it was more likely being abstracted from sand and gravel). A second phase of exploration well drilling was required, and this time drilling would target locations along the full extent of the course with little thought for piping and electrical costs. Phase two drilling confirmed the findings of the first phase of work, in that ground conditions generally encountered low permeability boulder clay, overlying weathered rock, with less than 1 m$^3$/hour of groundwater present in 4 out of the six wells.

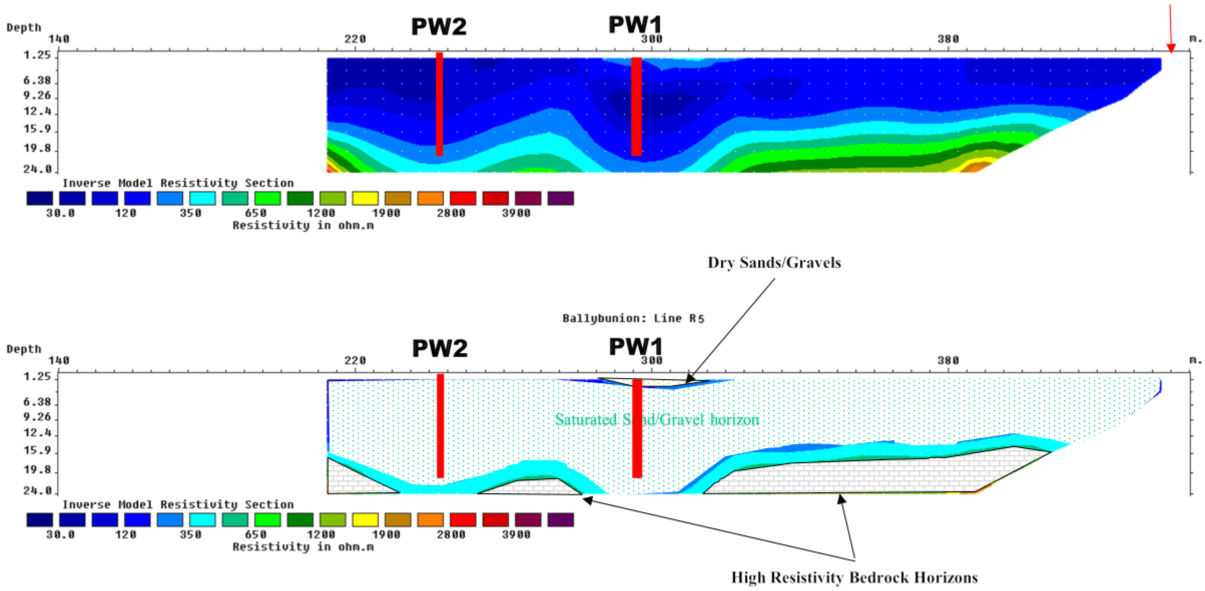


***Figure 3:*** *Geophysical Section Line Interpretation through Borehole Locations PW1 and PW2 south of club house (Source: BRG 2016)*

However, two locations of interest on the Cashen Course were also explored during phase 2. The geophysical survey appeared to show that bedrock was generally flat, and about 20m below ground level. But two v-notch incisions were noted south of the club house. When drilled, these incisions revealed the presence of medium to coarse sand with rounded gravel pebbles and large cobbles, from 13m to 17m BGL in PW1 and from 9.5m to 18m BGL in PW2. There was 60m separation distance between both wells. Yield estimates during drilling indicated the presence of more than 10m$^3$/hour from each of the wells, with minimal interaction between wells. It is thought the V-Notches in the rock represent paleo-river bed channels.

## TEST PUMPING AND SALINITY

Step test pumping confirmed that up to 22.5m$^3$/hour with 3m drawdown was possible from the future PW1, and 21.6m$^3$/hour with 2.2m drawdown was possible from the future PW2. Given the proximity of the wells to the coast (c. 460m), a 4 week constant rate pumping test was undertaken in late summer of 2017 to prove the yield. The electrical conductivity of water from PW1 remained relatively constant at between 800 and 900 µS/cm during the month of constant pumping. However, when the abstraction rate from PW2 was increased from 10 m$^3$/hour to 14 m$^3$/hour after 16 days of constant pumping, the electrical conductivity of the water from PW2 began to rise, and continued to rise steadily from 739 µS/cm to 1236 µS/cm after 30 days of constant pumping (Figure 4). 1236 µS/cm is still considered to be fresh water, however the upward trend in electrical conductivity with pumping is a cause for concern.

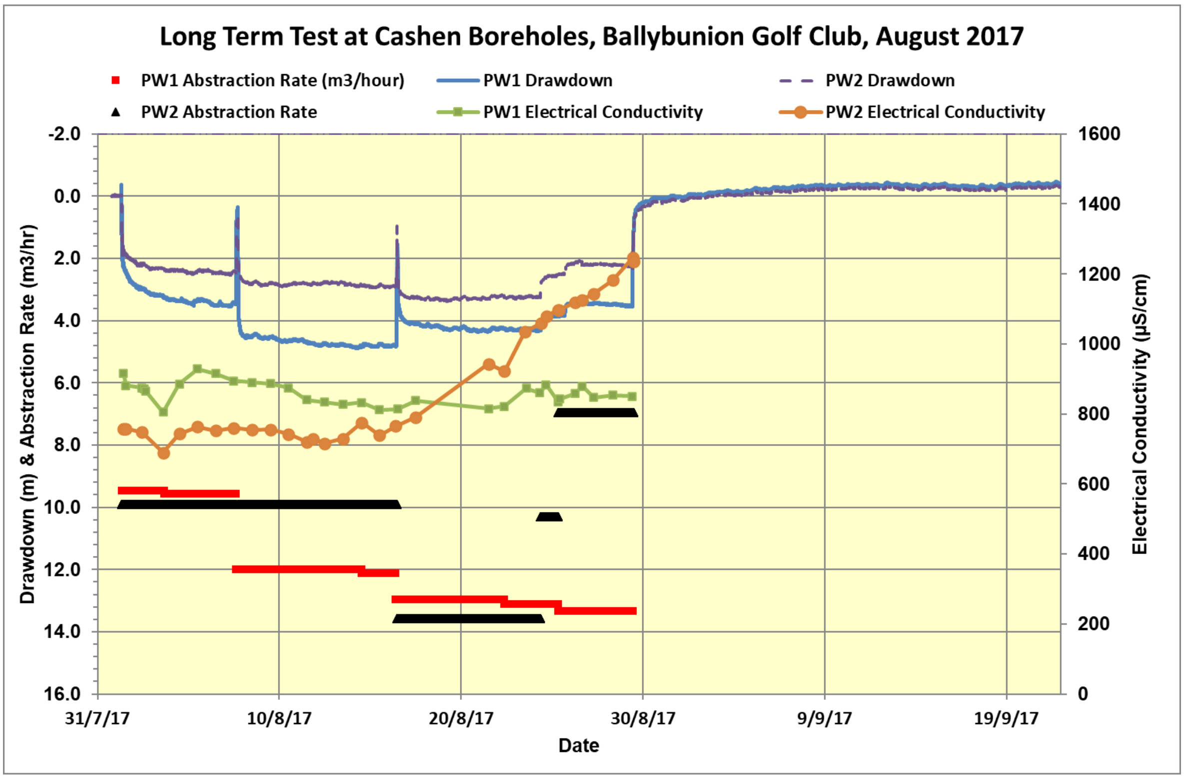


***Figure 4:*** *Long term test pumping of PW1 and PW2*

## WATER QUALITY

Groundwater samples were collected from each of the five wells weekly during the constant rate pumping test and analysed for pH, Electrical Conductivity, Major Ions, Iron and Manganese.

Chemical water quality is generally good, with groundwater analysis complying with the E.U. Drinking Water Standards, except for exceedances in Iron and Manganese.

The analysis clearly confirms that there is a lot more Iron and Manganese present in the boreholes on the Old Course, which abstract groundwater from the weathered rock, than in the Cashen Boreholes, which abstract from sand and gravel. A comparison of the average iron and manganese levels recorded in samples during test pumping confirms that the highest level of iron and manganese is found in the existing and oldest borehole, BH101 at the 4$^{th}$ tee. Average iron levels found in each borehole have been compared with the iron level found in BH101 (7.3 mg/l). The average iron level recorded in PW3 is 33.9%; the average iron level in PW4 is 70%; the average iron level in PW1 is 7%; and the average iron level in PW2 is 1.6% of the level recorded in BH101.

IRON ISSUES

Iron biofouling has been causing some difficulties in the management of Ballybunion golf course. Iron precipitate tends to fill the above ground storage tanks and clog sprinkler heads which are used to irrigate the greens. Iron related problems are not uncommon in north Kerry groundwater supplies due to the presence of naturally occurring iron in the water, which is abstracted from shaley limestone bedrock, and over pumping of boreholes. Water supply wells, pumps and pipelines need regular maintenance to prevent failure of boreholes and or pumps from iron related issues, as iron bacterial slimes can clog well screens and bedrock fractures, reducing the efficiency of groundwater wells.

PUMPING PROCEDURE CAN EXACERBATE IRON BIOFOULING

Turning on a pump for a short period of time at a high pumping rate creates excessive drawdown and gives the bacteria in the well a “gulp” of air. Then the pump is turned off and the bacteria get a shot of water containing ferrous iron. This process is repeated day after day as the borehole is over pumped each time.

Over-pumping a borehole by allowing groundwater cascade into the borehole, as is happening at the existing BH101, perpetuates this problem by further oxygenating the water column.

Ideally each borehole should be pumped at a sustainable level, which does not allow groundwater to cascade into the borehole, or expose the well screen to the atmosphere.

## BOREHOLE DESIGN

Two distinct borehole designs were applied in Ballybunion. One for the weathered rock wells (PW3 and PW4) , and another for the sand and gravel wells (PW1 and PW2).

The boreholes were drilled using a Knebel Rig, mounted on a Mercedes Unimog. This rig is especially set up to drill in sand and gravels using the symmetrex system, by allowing 200mm diameter steel casing to be installed as the 218mm borehole is drilled, thereby preventing sands and gravels from falling in on top of the drill bit and hammer, and keeping the borehole open. This drilling method was used to construct PW1 and PW2 which abstract ground water from sand and gravel beneath the Cashen course. Once the target drill depth has been reached, the drill bit, hammer and drilling rods are removed, and a 140mm outer diameter well casing and screen is installed within the steel casing. The steel casing is carefully removed from the borehole, as a properly designed fine sand filter pack is placed (by slowly pouring the sand in from the ground surface) into the annular space (the space between the steel casing and the well screen). The combination of the fine well screen slot size (1mm) and the properly designed fine sand filter pack (2mm to 3.5mm) allows water to move efficiently into the borehole, without pulling fine sand from the aquifer formation into the borehole and the water distribution network.

Once the boreholes were installed, the screen section of each borehole was developed using a purpose made packer tool. The packer tool allowed each half metre section of screen to be developed by pumping using compressed air to remove fines from the aquifer formation. This method of packer pumping “stressed” each half metre of screened section by pumping from that section at a much higher rate than expected when using a submersible pump. Once the submersible pump is installed, the well will be much less “stressed” than during well development works, allowing water without sand to be abstracted from the borehole.

PW3 and PW4 abstract groundwater from bedrock rather than from sand and gravel. The same drilling method as above was used to drill through the overburden and to reach to top of bedrock. Once bedrock was encountered the borehole was drilled open hole (without advancing the steel casing). As with the method above, once the target drill depth has been reached, the drill bit, hammer and drilling rods are removed, and a 140mm outer diameter well casing and screen is installed within the steel casing. The screened section is installed within the open-hole section of bedrock and the annular space was filled with 6mm pea gravel. This design was chosen to allow the installation of a bentonite seal between the top of the bedrock and the overburden to prevent washing fine silt into the boreholes during pumping. The annular space from between the top of the bentonite seal and ground-level was backfilled with spoil from the drilling process. These boreholes were also developed using the drilling rig and compressed air to clean out the fractures in the rock and allow clean water (without sediment) to be abstracted from the boreholes.

## COUNTY LOUTH GOLF CLUB, BALTRAY

County Louth Golf Course occupies an area of approximately 77 hectares and is located on the northern bank of the Boyne Estuary c. 6.5km north east of Drogheda, Co. Louth. The course is situated on sand dunes in the townland of Baltray, by which name the course is more commonly known. The course is bound by the Irish Sea to the east, by agricultural tillage land to the west, by the Boyne Estuary to the southwest and by Seapoint Golf Club to the north. Agricultural and neighbouring groundwater users are competing for the same groundwater resource. A brackish or saline lagoon is located southeast of the course.

The existing water supply was sourced from two shallow dug wells, roughly 6.7m x 6.7m x 2m deep, constructed c. 35 years ago. The wells are located between 300m and 600m from the coast. One of the wells is high yielding ( c. 30 $m^3$/hour), the other a low yielding well. Both are starting to fall into a state of disrepair and need upgrading or replacement. The maximum water demand is c. 42 $m^3$/hour.

Given the high yield being abstracted from Well 1, it was always assumed that the well was being fed by permeable gravels (Figure 5). The thickness of the underlying gravels was unknown, and it was also not known whether the gravels were underlain by low permeability clays, or lying directly on bedrock.

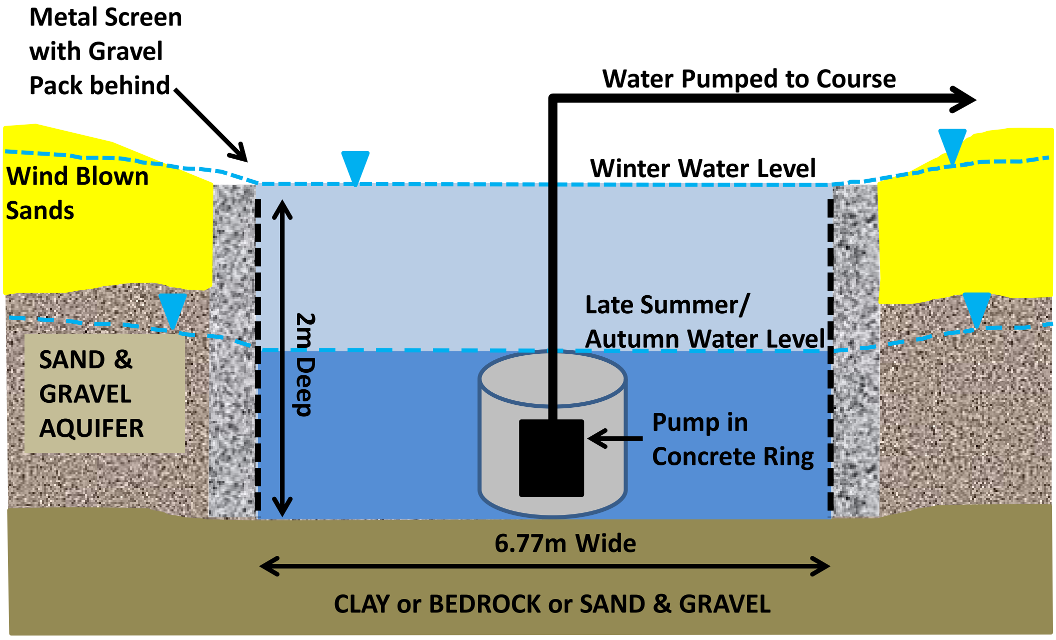


***Figure 5:*** *Schematic of Well 1 with possible geology (to be confirmed by geophysical survey and drilling)*

A desk study review of available GSI maps indicated that the course was partially underlain by the Clogher Head Gravels, which are classified by the GSI as a locally important gravel aquifer, indicating possible well yields of up to 400 $m^3$/day (this designation was removed from the online web mapping tool post 2019). The underlying bedrock is classified as a Regionally Important Kastified Aquifer by the GSI. This indicates possible bedrock well yields of greater than 400 $m^3$/day.

It was reported that an exploration well had been drilled close to Well 1, but that water from the well was saline and it had to be abandoned. It is assumed this well was drilled into bedrock, or into a gravel layer containing saline water. No logs were available.

Given the hydrogeological setting, and the risk of abstracting saline water, it was decided to proceed with a geophysical survey in advance of exploration well drilling. The aims of the geophysical survey were to determine the variation in thickness of the saturated sands and gravels, and the position of the fresh water lens and fresh water salt water interface within the saturated sands and gravels, and to try and identify any potential water bearing structures in the top of the underlying limestone bedrock aquifer, before embarking on an exploration drilling programme.

## GEOPHYSICAL SURVEY AND EXPLORATION WELL DRILLING

The geophysical survey indicates a depth to bedrock of between 30 to 40 metres, with dry sands to 5 metres below ground level, saturated sands or gravel between 10 to 15 metres below ground level. Beneath the sands and/or gravels in most sections is a very low resistivity layer, was interpreted as being low permeability boulder clay, or, unconsolidated sand and gravel with salt water. Exploration drill holes were picked based on analysis of the geophysical survey results.

Exploration well drilling confirms that the course is underlain by between 8.8m (beneath the nursery area) and greater than 18.2m and of water bearing unconsolidated sediments (south of Well 1). The unconsolidated sediments consist of fine sands, sandy gravels and fine to coarse gravels with cobbles which are underlain by low permeability silty clay in TW101 and TW102. The depth to the clay horizon increases from north to south towards the Boyne estuary, which bounds the southern end of the course. The clay horizon was not encountered in TW103 or TW104 which were drilled to depths of 15.6m and 18.2m BGL respectively.

Step testing, confirms the presence of high yielding wells, with two of the 4 wells yielding 17$m^3$/hour with less than 0.15m drawdown. No drawdown was noted in any of the other wells during pumping. The salinity levels in all boreholes remained relatively stable during short term step test pumping (680 to 850 μS/cm). There was no evidence of saline intrusion during test pumping (with the exception of water with slightly elevated electrical conductivity encountered at depth in TW104 (electrical conductivity of 1200 μS/cm – though water from this well became less mineralised with pumping). Groundwater quality beneath the course is generally good, with no elevated levels of iron in the water.

Production wells were designed based on the information uncovered during the exploration well drilling programme (i.e. test pumping data and grain size analysis of the sediments). Four production wells were installed in order to secure a sustainable groundwater supply for irrigation at County Louth Golf Club. Production well design allows for an abstraction rate of 12 $m^3$/day per borehole. Each well is capable of producing much more than that, however, given the proximity to the coast, it is suggested to limit the abstraction in order to sip gently from 4 wells, rather than pumping hard from one. The production wells were drilled at 200mm diameter to facilitate the installation of a filter pack to prevent fine sands from entering the well, and will allow more water in with less drawdown in water level.

## ROYAL COUNTY DOWN CASE STUDY

Royal County Down Golf Club is located in sand dunes immediately north of the Mourne Mountains, in Newcastle, Co. Down. The site is bounded by the Irish Sea to the east. A desk study review of information available from the Geological Survey of Northern Ireland (GSNI) indicates there are two potential aquifers beneath the site:

- A shallow windblown sand and gravel aquifer; and
- A deeper sandstone bedrock aquifer.

The maximum water demand is c. 25 $m^3$/hour. There were two existing wells on the site, both relatively shallow and abstracting water from the sand and gravel aquifer. The first well was drilled to a depth of 13m in 1991 c. 300m from the coast. Permeable sand and gravel was encountered, overlying low permeability silt and clay from 12 to 13m BGL.

A second well was drilled c. 400m to the north of the first well in 1999, c. 470m from the coast. Similar strata was encountered in Well 2, except that the well was completed in a second gravel layer at 14m BGL. Both wells were completed at 250mm diameter, with 3m of stainless steel wire wrap screen with a 2.5mm slot size, allowing a natural filter pack to develop. Both wells were test pumped at c. 16 $m^3$/hour with less than 1m drawdown. Elevated iron (5.6 mg/l) was detected in Well 2 when sampled in 2000.

The hydrogeologist at the time proposed restricting the abstraction to 10 $m^3$/hour per well to keep a positive head gradient in relation to sea level, in order to minimise the risk of saline intrusion.

A geophysical survey was carried out by Minerex in 2020 with a view to developing addition water supply wells for the course (at that stage the club had been informed incorrectly that Well 2 had collapsed and needed to be replaced). The survey indicated up to 19m of sands and gravels overlying silt clay beneath the northwestern portion of the course.

### EXPLORATION/PRODUCTION WELL DRILLING AND TESTING IN 2022

The target locations identified during the geophysical survey were not drilled due to distance back to the reservoir tank. Instead, two new abstraction wells were drilled in February 2022. Well 3 was drilled to a depth of 14m BGL beside the existing irrigation storage reservoir to explore groundwater conditions at this location, c. 280m from the beach. Well 4 was drilled to a depth of 10m BGL c. 150m north of Well 2 (drilling was unable to advance any deeper due to the presence of large cobbles). Subsequent particle size distribution analysis indicates a natural filter pack could have been developed for both of these wells.

These wells were drilled without completing exploration drilling in advance. Therefore, a conservative well design was used. Three metres of 140mm OD stainless steel wire wrap screen with 1mm slots, and a 2 to 3.15 mm silica filter sand, were installed in each of the wells.

Test pumping of the wells indicates these wells can be pumped at up to 16 $m^3$/hour with 1m drawdown in Well 3 and 0.37m drawdown in Well 4.

### CONCEPTUAL MODEL

Production well drilling indicates that the course is underlain by at least 15m of water bearing unconsolidated sediments (the depth to consolidated sediments or the bedrock was not proven during drilling in February 2022). The unconsolidated sediments consist of fine sands and coarse sandy gravel which are underlain by low permeability boulder clay. The depth to the boulder clay horizon is highly variable from south to north and from east to west according to the geophysical survey. Boulder clay was not encountered in Well 3 close to the reservoir tank or Well 4 south of the practice area, which were each drilled to 15m and 10 metres below ground level (mBGL) respectively. It is assumed that the boulder clay is present at depth beneath both of these wells (This may or may not be the case). Normally the presence of boulder clay beneath the sands and overlying the bedrock offers a natural protection to help prevent up-coning of heavier salt water during groundwater abstraction. No bedrock was encountered during drilling activities on the site.

Analysis of water quality on the site using a pH/Electrical Conductivity/Temperature probe indicates that the groundwater within the unconsolidated sediments is fresh with electrical conductivities in the range of 363 µS/cm in Well 3 and 317 µS/cm in Well 4.

The sands and gravels underlying Royal County Down will be replenished as rainfall percolates into the ground; from water percolating to ground from the rivers, streams and drains that cross the sands and gravels, and possibly, from groundwater upwelling from the underlying bedrock aquifer.

## FINDINGS

Fresh water lenses are present within the sand and gravel deposits around the coast in Ireland. Groundwater within these deposits is replenished by rainfall and seepage from rivers and streams that cross the sand and gravel deposits. Many of the coastal aquifers are underlain by low permeability silts and clays, which protect the sand and gravel deposits from up-coning of saline water, which is often present in the underlying bedrock aquifers.

It is usually easier to abstract fresh water supplies from sand and gravel aquifers close to the coast than from the underlying bedrock aquifers. There is a much higher risk of pumping saline water from bedrock wells close to the coast than from sand and gravel aquifers. Sand and gravel aquifers tend to have a significant portion of the aquifer sediments above sea level. Maintaining a positive head gradient can prevent inducing salt water into these aquifers.

Bedrock wells can intercept fractures which are directly linked to the sea; pumping groundwater from bedrock wells can very quickly draw salt water into the wells, such as occurred in Ballybunion, Portmarnock, and reportedly occurred in Baltray. A notable exception are the two bedrock wells serving Trump International at Doonbeg. In these wells a combination of bedding and low permeability shale rock layers dipping out to sea appears to prevent salt water ingress, despite being located within 300m of the shore.

Most courses require between 20 and 50 $m^3$/hour for irrigation purposes. This level of abstraction is not required year round. Most courses abstract no groundwater between November and the end of March. Continuous pumping usually occurs only during extended dry periods between April and October inclusive. During normal Irish weather conditions, intermittent pumping is the norm as water is needed for spot treatments, turf maintenance and repair of damaged turf.

An abstraction of 20 to 50 $m^3$/hour is eminently feasible to abstract from gravels, and even from fine silty sands (more wells will be required), and usually accounts for a small fraction of the available water balance. Notwithstanding the large volumes of available water present within the underlying coastal aquifers, consideration must be given to other nearby groundwater users (sometimes neighbouring golf courses, or farms).

The coastal aquifers are often only 5 to 10m in thickness. Well designs need to take account of the small saturated thickness. Screens with a large open area are used to minimise drawdown. Abstraction rates are chosen to prevent the wells screens being exposed to the atmosphere, where possible. Abstraction rates are often limited to prevent a concentration of well pumping from one area. “Sipping gently” from three or four or more wells is preferred, than “guzzling” hard from one.

Iron and manganese issues are common on the west coast (Lahinch, Doonbeg, Ballybunion). Calcium carbonate build up can impact wells in lime rich areas such as Royal Portrush. Therefore, wells have been designed with borehole maintenance in mind, in particular to allow redevelopment works and chemical treatment. The aim of the maintenance programme is to prevent the build-up of slimes, encrustations and subsequent plugging of boreholes.

The impact of groundwater abstractions from golf links courses on water levels in the underlying aquifers tends to be minimal and localised for the following reasons:

- A high percentage of irrigation water is returned to the underlying aquifer via percolation
- Irrigation water is usually applied at night to limit transpiration and evaporation losses (and when the course is not in use)
- Course managers apply the minimum amount of water required to keep the grass and turf healthy as golfers like to play links golf on a hard dry surface rather than a saturated soft surface.

The impact on groundwater dependent habitats can be managed. In fine sands, the radius of influence of groundwater wells is often between 80m to 100m. When abstracting from weathered rock, or a thin gravel layer, the radius of influence can be much longer. Humid dune slacks, the main habitat of concern in sand dunes, are wet only in winter, when no abstractions take place.

All sites are very different and have different characteristics. Each site should be approached with an open mind, and be prepared for conceptual models to be challenged and revised as each phase of work develops.

## ACKNOWLEDGEMENTS

Thanks to David Ball for his assistance and mentoring, especially when working on the Portmarnock Golf Course. Thanks also to Stephan Petersen, of Petersen Well Drilling who has drilled and installed the boreholes. Thanks to Ballybunion Golf Club, County Louth Golf Club and Royal County Down Golf Club for kindly permitting me to share some of the learnings from their courses.

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# REWET: Hydrologic impacts of water table management on grassland peat soils

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The artificial drainage of carbon-rich peat soils is a common practice to increase agronomic production on waterlogged lands but may lead to the release of carbon dioxide to the atmosphere. In Ireland, there are an estimated 300-350,000 ha of permanent grassland on peat soils, with varying degrees of drainage. The National Climate Action Plan is targeting 80,000 ha of such soils for 'reduced management intensity'. This process may involve the removal or blocking of existing artificial drainage features, often referred to as 'rewetting' or 'active water table management'. Research has found that every 10 cm the water table is raised has a positive impact in reducing the net warming impact of greenhouse gas emissions.

The Department of Agriculture, Food and the Marine-funded project, REWET, aims to provide a deeper understanding of the hydrologic impacts of water table management on grassland peat soils. To achieve this goal, ten field sites on grassland farms with varied enterprises and intensity were selected and classified into peatland type. Each site is instrumented with rainfall gauges, dipwells with pressure sensors to monitor the water table position, multi-depth soil moisture probes and, at some sites, ditch blocking infrastructure and flumes to raise the water table and measure drainage discharge. Ultimately, the combined dataset will establish factors of importance that influence site suitability for rewetting. Such results will inform water table management strategies to reduce the impact of greenhouse gas emissions on the environment and support sustainable land management practices on grassland peat soils.

# SESSION IV

# TESTING-THE-WATERS: PREDICTION OF HIGH FLOW EVENTS IN BLANKET BOG CATCHMENTS USING SUPPORT VECTOR MACHINES (SVM) FOR AUTOMATED EVENT WATER SAMPLING

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## ABSTRACT

*Peatlands are estimated to cover approximately 20% of Ireland, with blanket bogs accounting for 13%. High-resolution hydrological monitoring is key to establishing baselines for determining impacts of blanket bog rewetting. Blanket bogs are prone to flashy runoff regimes, where storm flow accounts for the bulk of runoff and aqueous carbon export. However, their short time to peak can lead to delays in capturing entire event hydrographs. In addition, their often isolated location can hinder both access to and remote communication with devices. Machine learning algorithms (MLA) offers a dynamic, data-driven method for catchment monitoring. High-resolution runoff, precipitation and barometric pressure data were collected over two years at Letterunshin, Co. Sligo. These data are used to develop a binary classification model using Support Vector Machines (SVM) to predict the occurrence of high flow events. This prediction together with our telecommunications network serves to trigger an autosampler array for targeted event sampling. Here, we present the process of data preparation, parameter selection and the development of a SVM algorithm with performance accuracy > 90%. This research underpins the management of water resources derived from blanket bogs, their runoff and water quality monitoring applications within an Irish context.*

**Key words:** Peatland, blanket bog, hydrology, Machine Learning Algorithms, Support Vector Machines

## INTRODUCTION

Peatlands cover approximately 20% of Ireland, with blanket bog being the most extensive peatland type and making up 13% of the country (Joosten *et al.*, 2017). Yet, peat extraction and degradation have meant that only about 28% of the original blanket bog cover remains as actively accumulating mire in Ireland (Joosten *et al.*, 2017). Blanket mires maintain a water table at or near the surface for most of the year, supported by regular precipitation typically above 1,200 mm/year and with at least 225 rain days (Hammond, 1981). The waterlogged condition and sloping topography make blanket mire prone to a flashy runoff regime, with storm hydrographs typically characterised by a short time-to-peak. In addition, stormflow tends to account for the bulk of annual runoff.

High-resolution, long-term monitoring of peatland hydrology is essential for assessing short- and long-term trends in their hydrological functioning, particularly in response to natural processes, human activities, restoration and climate change. Despite technological advances in sensor technologies over recent decades, the flashy nature of the blanket mire hydrology can lead to difficulties in obtaining accurate runoff estimates during high flow events. Short lag times within the rainfall-runoff behaviour (e.g. time-to-peak) can lead to peak flow being missed between sensor recording intervals, resulting in an underestimation of stormflow. In addition, long-term monitoring of blanket mires is often hindered due to their remote location impeding access to and remote communication with monitoring devices. Moreover, the challenge in accessing peak flow not only affect the accuracy of hydrological budgets, but also the biogeochemical flux estimations, such as nutrients and dissolved organic carbon (DOC).

Physically based modes have long been used in rainfall-runoff modelling and the prediction of hydrological events, but often require complex datasets and intensive computation, impeding short-term flow prediction (Mosavi *et al.*, 2018). More recently, advanced data-driven methods, such as Machine Learning (ML), have rapidly grown to a mainstream approach in hydrological modelling (Langhammer, 2023). ML is a subset of artificial intelligence (AI) that comprises learning methods and algorithms which enable computers to automatically improve performance through experience. Machine learning algorithms (MLA) (*Figure 1*) are formulated on a data-based, rather than knowledge-based, method. As such, MLA are a highly dynamic and computationally-efficient method, relying on historical data, and do not require in-depth knowledge about the underlying physical processes (Mosavi *et al.*, 2018). Here, we apply a binary Support Vector Machine (SVM), a type of supervised MLA, to classify high flow events solely based on available discharge, precipitation and barometric pressure data from a blanket bog catchment in Co Sligo.

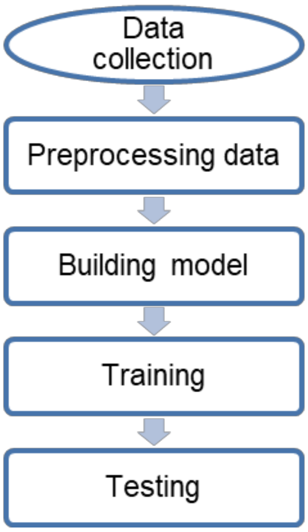


***Figure 1:*** *The workflow of building a machine learning algorithm (MLA). Adapted from Mosavi et al., (2018).*

## METHOD

### SITE AND DATA COLLECTION

The Letterunshin Blanket Bog Hydrological Research Catchment (Letterunshin) is situated in the foothills of the Ox Mountains in Co Sligo. The peat deposits initiated on top of the Dinantian upper Ballina limestone formation, with the immediate substrate consisting of till derived from metamorphic rocks (TMp) (Flynn *et al.*, 2022). The thickness of the peat deposit extends in excess of 6 meters and site observations have revealed extensive peat piping. The site receives a mean annual rainfall of 1105 mm/year and limited groundwater recharge of 44 mm/year (Flynn *et al.*, 2022). The relatively intact blanket peat catchment (160.3 ha) is drained by the Fiddanduff River, while the lower catchment (54.2 ha) is degraded due to drainage and forestry.

Hourly precipitation, barometric pressure and discharge data were collected over the 2017/18 and 2018/19 hydrological years. Precipitation and barometric pressure data were collected by a Davis Vantage Pro Plus 2 tipping bucket and weather station, installed within the Fiddanduff catchment area of intact peat. A flume and stage installation in the Fiddanduff river, within the area of intact blanket peat, were used to related spot measurements of river stage to discharge over the range of flow conditions experienced during the monitoring period (April 2018 – April 2020). Rating curves were generated based on spot dilution gauging using saline tracer at the flume installation. A non-vented level logger (Solinst, Waterloo, ONT) with a 1 m measurement range, allowed for semi-continuous stage monitoring and the generation of semi-continuous stream discharge at 1-hour intervals.

## BASEFLOW SEPARARTION AND EVENT CLASSIFICATION

The MATLAB toolbox HydRun (Tang and Carey, 2017) was used for rainfall-runoff analysis and flow separation of Letterunshin discharge data from the 2017/18 and 2018/19 hydrological years (*Figure 2*). HydRun uses routines to extract baseflow from the hydrograph and compute time instants of the rainfall–runoff relationship, while allowing the user to decide thresholds and limits of analysis. For example, among other user-defined parameters, storm hydrographs are extracted based on a ‘peak threshold’ which is used to identify events that reach that minimum level of discharge. Minor events and fluctuations are thereby ignored (Tang and Carey, 2017). Here, we assigned the ‘peak threshold’ as the Q10 (90$^{th}$ percentile, 0.0949 $m^3/s$) high-flow indicator, based on the mean from 2017/18 and 2018/19 discharges.

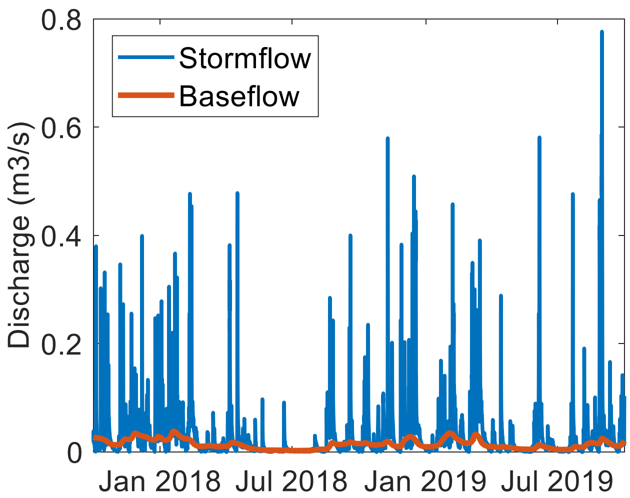


***Figure 2:*** *Stormflow and baseflow ($m^3/s$) extracted by HydRun (Tang and Carey, 2017) based on the Letterunshin discharge ($m^3/s$) timeseries (October 2017 – September 2019).*

## FEATURE SELECTION

Discharge, precipitation and barometric data were pre-processed to produce features signifying a range in timescales leading up to storm event. Features were thus made up of discharge, precipitation and barometric pressure data at 1-hour intervals and 3- and 6-hour moving averages (or moving sums in the case of precipitation), producing a total of 15 features (*Table 1*). A principal components analysis (PCA) between all features indicated that the first two components explain 95.6% of total variation (PC1 = 60.1%; PC2 = 35.5%). The two most important features were identified by ranking using the Minimum Redundancy Maximum Relevance (MRMR) algorithm which may be applied to classification problems.

The MRMR algorithm identified Precip-6 and StormFlow-6 as most important features (*Figure 3*).

***Table 1:*** *Features included during the intitial feature selection and their descriptions*

| Feature | Description |
|---|---|
| TF-1 | Total flow hourly data |
| TF-3 | Total flow 3-hour moving average |
| TF-6 | Total flow 6-hour moving average |
| BF-1 | Baseflow hourly data |
| BF-3 | Baseflow 3-hour moving average |
| BF-6 | Baseflow 6-hour moving average |
| SF-1 | Stormflow hourly data |
| SF-3 | Stormflow 3-hour moving average |
| SF-6 | Stormflow 6-hour moving average |
| Baro-1 | Barometric pressure hourly data |
| Baro-3 | Barometric pressure 3-hour moving average |
| Baro-6 | Barometric pressure 6-hour moving average |
| Precip-1 | Precipitation hourly data |
| Precip-3 | Precipitation 3-hour moving sum |
| Precip-6 | Precipitation 6-hour moving sum |

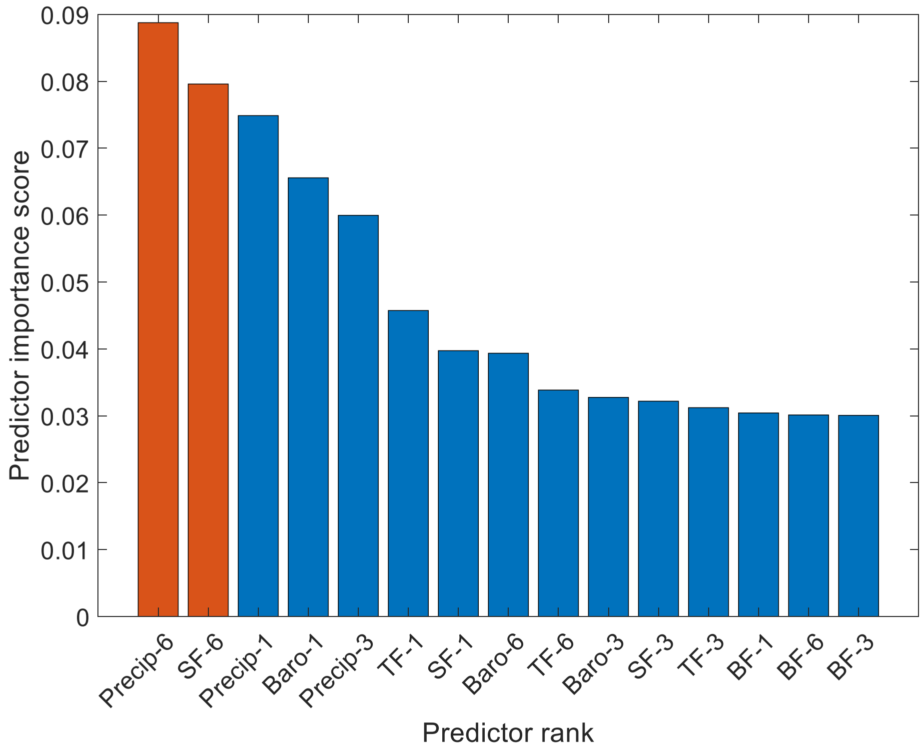


***Figure 3:*** *Feature selection from predictor importance scores based on the minimum redundancy maximum relevance (MRMR) algorithm. The two highest ranking features, Precip-6 and SF-6, are highlighted in red and together explain over 95% of variation.*

## DEVELOPMENT OF A SUPPORT VECTOR MACHINE (SVM) ALGORITHM

Support Vector Machines (SVM) is a supervised MLA that is typically applied within classification problems. The SVM identifies a hyperplane that separates one class of data from another. The "best" hyperplane has the widest margin between different classes. An added benefit of SVM is that it offers kernel function choices for greater accuracy. The 'kernel trick' allows features to be transformed to a higher dimensional space using a kernel function for easier separation of classes, while remaining computationally efficient.

Data were separated by hydrological year into a training set (2017/18) and testing set (2018/19). Using the training set, SVMs were trialled with the two selected features, Precip-6 and SF-6. The algorithm was fine-tuned by adjusting the kernel scale, box constraint and misclassification cost. The kernel scale enables the SVM to classify data points that do not separate linearly, i.e. it maps a non-linear hyperplane. The box constraint helps prevent overfitting by determining the maximum penalty imposed on margin-violating observations, with a larger box constraint resulting in fewer support vectors. A smaller box constraint is particularly fitting when data classes are not perfectly separable, and some misclassification must be permitted to prevent overfitting. Finally, the misclassification cost applies a penalty for misclassifying data. As data were heavily skewed towards the 'no event' class, a misclassification cost was added for the misclassification of 'event' as 'no event'.

## RESULTS

### EVENT STATISTICS AND CHARACTERISTICS

A total of 55 events were identified over the two-year monitoring period, 27 in 2017/18 and 28 in 2018/19. The bulk of events occurred in the months October, November, December and January, with March also characterised by a relatively high number of events solely during 2018/19. April, June and July contained up to one event every year, while no events were identified in May (*Figure 4*).

During the events, effective precipitation ranged between 8 and 61 mm (mean = 23 mm), lasting 8 – 104 hours (mean = 29 hours). The time base of the hydrograph, between the beginning and end of event flow, lasted 15 – 157 hours (mean = 52 hours). The time of rise between the beginning and peak of the event flow varied between 4 and 48 hours (mean = 15 hours), while the lag to peak between the beginning of effective precipitation and peak event flow spanned 6 – 61 hours (mean = 19 hours).

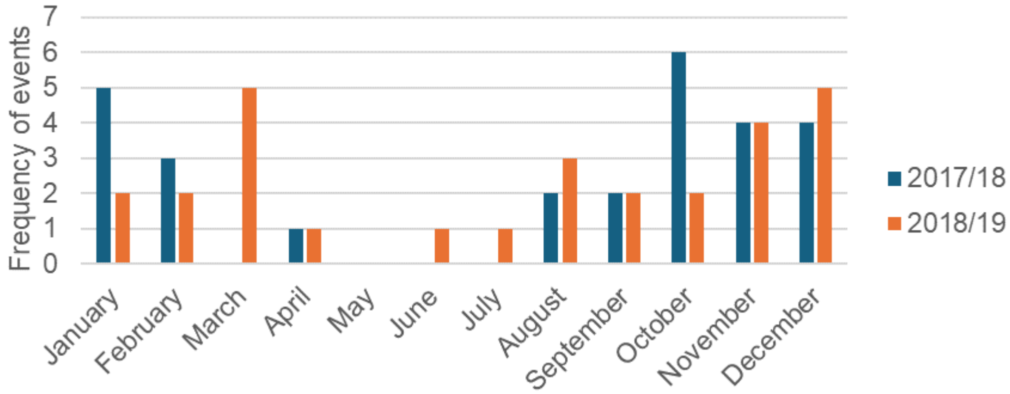


***Figure 4:*** *Frequency of events in each month organised by hydrological year.*

### EVENT CLASSIFICATION

A SVM algorithm was produced using the training set from 2017/18, with 10-fold cross-validation. The optimum configuration had an adjusted Kernel scale 1.7, box constraint 0.3 and misclassification cost factor 2.5 ('event' misclassified as 'no event'). The generalisation error, which measures the rate at which the algorithm misclassifies the outcome ('event' or 'no event') in new data, was 4.6%. The algorithm accuracy rate of the training set was thus 95.4% (*Figure 5*). The receiver operating characteristic (ROC) curve showed an area under the curve (AUC) value of 0.8829. Applying the algorithm to the testing set indicated good repeatability, with a generalisation error of 5.9% (algorithm accuracy = 94.1%) (*Figure 6*). Similarly, the AUC of the testing set was 0.8918. Our results generally corroborate the accuracy and robustness of SVMs in hydrological classification as found by others (Langhammer, 2023).

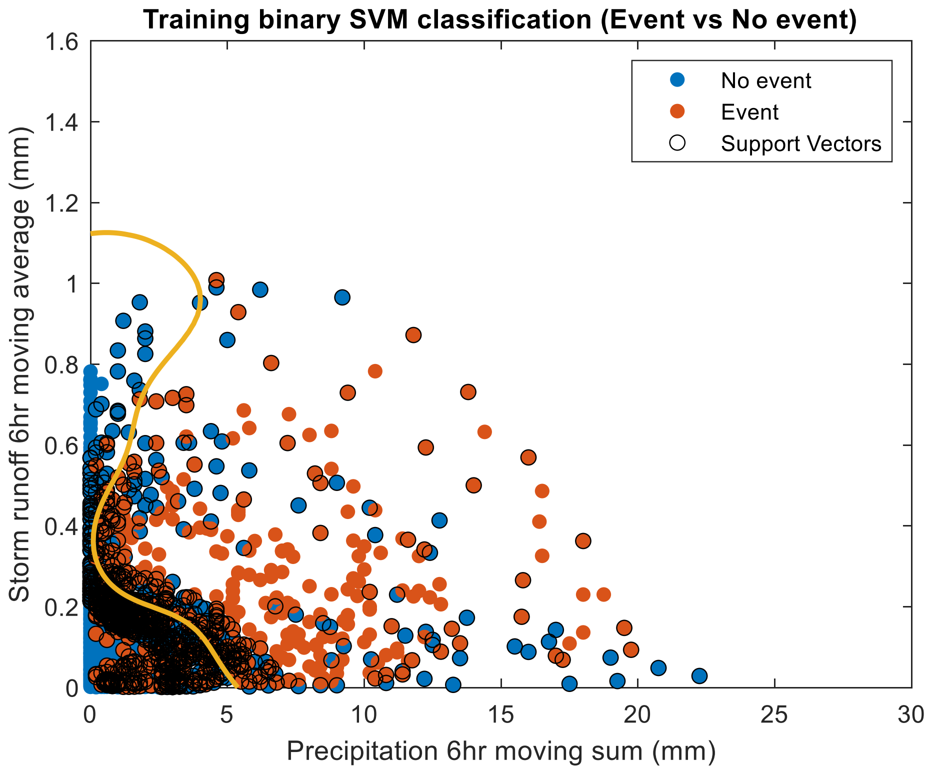


***Figure 5:*** *Training data for event (no event) classification based on the precipitation 6 hour moving sum and storm runoff 6 hour moving average. The orange line signifies the hyperplane.*

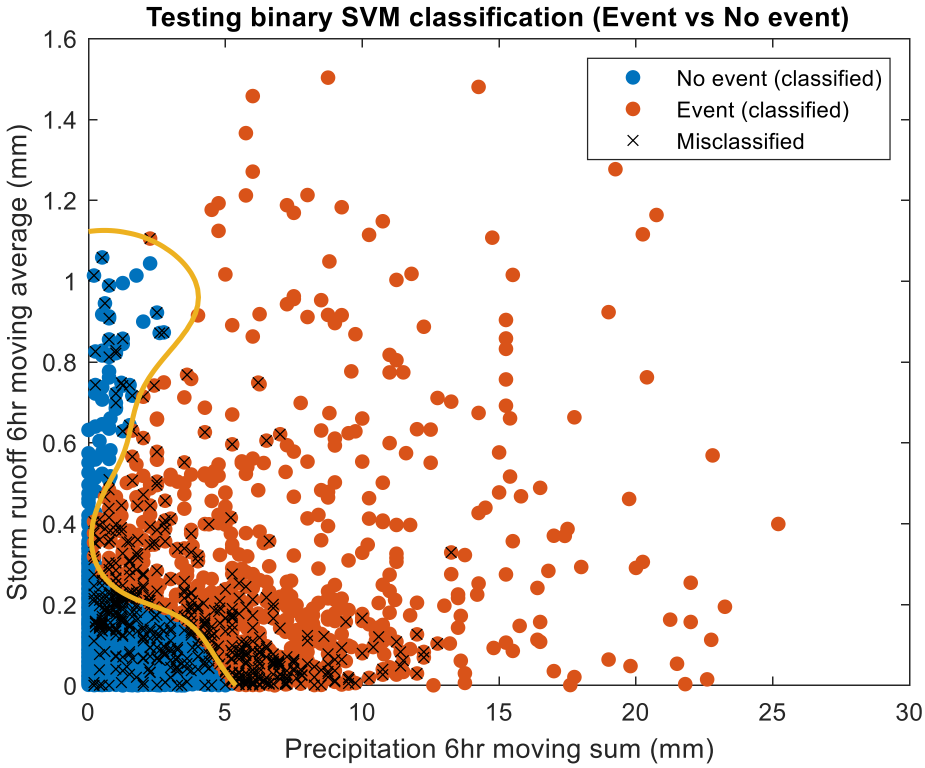


***Figure 6:*** *Testing data for event (no event) classification based on the precipitation 6 hour moving sum and storm runoff 6 hour moving average. The orange line signifies the hyperplane.*

## CONCLUSION

The nature of blanket bog hydrolgical funtioning, particularly rainfall-runoff regimes, forms a challenge for effective hydrological and biogeochemical monitoring and flow prediction. Events identified at the Letterunshin blanket bog catchment over a two-year (2017/18 and 2018/19) monitoring period showed clear seasonal trends, with a high frequency of events in autumn and winter, while rare or negligible in late spring and summer. Precipitation and flow characteristics showed the range in timescales, sometimes limited to within 24 hours while other times extending beyond 6 days.

A SVM was trained using 2017/18 precipitation and stormflow data derived from Letterunshin. The SVM required optimisation by adjusting the kernel-scale, box constraint and misclassification cost, however then delivered a satisfactory accuracy rate of 95.4% with the training dataset. The algorithm furthermore showed satisfactory repeatability through the testing dataset, with an accuracy of 94.1%. Our results suggest that SVMs offer an efficient pathway for rapid, high-accuracy event classification under flashy flow conditions, with the potential for short-term flow prediction within a 6-hour timeframe. This research underpins the management of water resources derived from blanket bogs, their runoff and water quality monitoring applications within an Irish context.

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# A Research and Energy Production Geothermal Project on The TU Delft Campus: Project Implementation and Initial Data Collection

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## ABSTRACT

*A geothermal well doublet, designed with two primary aims; one of research and the second of commercial thermal energy supply, is currently being installed on the campus of Delft University of Technology, with the wells being drilled in the second half of 2023. The project includes a comprehensive research program, involving the installation of a wide range of instruments alongside an extensive logging and coring program and monitoring network. The doublet has been cored, with continuous samples from the heterogenous reservoir being complimented with more distributed side-wall cores, alongside a large suite of open-hole well logs in the reservoir section of both wells. Such investigation is rarely undertaken in geothermal projects. A fiber optic cable will monitor the production well, and will be installed all-the-way down to the reservoir section when the well completion is installed, at approximately 2300m depth. The reservoir is the fluvial Lower Cretaceous Delft Sandstone that is used as a geothermal reservoir in a series of existing and planned doublets in the West Netherlands Basin. A local seismic monitoring network has been installed in the surrounding area with the aim of monitoring very low-magnitude natural or induced seismicity. A vertical observation well with electromagnetic sensors will be drilled in a few years' time between the injector and producer to monitor cold-front propagation. The total project is targeted to supply around 25 MW of thermal energy at peak conditions, next to this project a thermal energy storage system is planned to provide a seasonal buffer. The project is a key national research infrastructure and is being incorporated into the European infrastructure EPOS (European Plate Observing System, https://www.epos-eu.org/), such that accessibility and data availability will be as wide as possible. All observations will be included in a digital-twin framework that will allow better decisions to be made in future geothermal projects. This paper presents the implementation and initial data collection from the project, including an initial evaluation of the logging and coring campaigns.*

**Keywords:** Field testing, Scientific drilling, Direct use geothermal, Case study, Field laboratory

## 1. INTRODUCTION

Nearly half of Netherlands' natural gas consumption is used for heating. Direct-use geothermal heating is one of the key available low-carbon energy solutions and is projected to cover around 30% of the demand which would result in around 700 direct-use doublets being installed in the Netherlands (Platform Geothermie et al., 2018). In the EU, it is projected that 25% of heating energy can come from geothermal energy, with 10% of the total demand coming from underground thermal energy storage (Ciucci, 2023). In the Netherlands, the vast majority of the existing (~20) projects supply thermal energy to the greenhouse farming sector, which has been a substantial success story, with further penetration in this sector projected in the coming years. However, urban heating supply (where the majority of the heating demand exists) has yet to be supplied in a major way.

At present the geothermal sector in the Netherlands is dynamic with >20 exploitation licences being granted annually; however, the current rate of drilling is between 1 and 2 doublets per year (NLOG, 2023). There are a multitude of interconnected reasons why this is the case, which range from key issues related to the behaviour of the subsurface, to surface plant and energy distribution facilities, and commercial arrangements. For example, induced seismicity is a major social-technical issue, as the Netherlands has extremely low natural seismicity and has suffered from increased seismicity induced due to gas extraction (Muntendam-Bos et al., 2022), and it is clear, as can be seen later in this paper, that to achieve the industry ambitions, geothermal doublets must be drilled close to each other in heterogeneous reservoirs, which can introduce interference (e.g. Wang et al., 2023). In addition, to decarbonise the heating sector, substantial advances need to be made in commercial (financial and contractual) arrangements, and in the integration of heating system components, including supply, distribution, storage and heat pumps.

In response to several of these challenges, and a desire to fully decarbonize the TU Delft campus by 2030 (van den Dobbelsteen and van Gameren, 2022), the Geothermie Delft (https://geothermiedelft.nl/en/) project was established with the dual aim to develop new scientific insights, methods and knowledge and to deliver thermal energy to the TU Delft campus and a portion of the city (Vardon et al., 2020). The project consists of a ~2.5 km deep geothermal doublet, with production and injection from the Delft sandstone, an early Cretaceous sedimentary fluvial deposit, in the West Netherlands Basin (Willems et al., 2020). The project will be operated by a commercial entity (a consortium of Aardyn, EBN, TU Delft and Shell Geothermal), with the first energy production planned in 2025. The doublet will be connected to a heating grid, an aquifer thermal energy storage system, and a heat pump to form a comprehensive urban heating system. In the second part of 2023, the doublet was drilled and a wealth of information collected. This paper gives an overview of the project, the scientific programme and the data collected during the drilling of the doublet.

## 2. PROJECT DESCRIPTION

The Geothermie Delft project, illustrated in Figure 1, consists of a doublet targeting the early Cretaceous Delft sandstone formation, which is located at approximately 2 km deep beneath the campus of Delft. The target reservoir location is situated within a syncline bounded to the south-west by a seismically inactive fault at approximately 1km distance and to the north-east by another seismically inactive fault at approximately 4km distance from the surface location (Figure 2). Both wells are deviated such that they move away from the closer fault and target a deeper (hotter) portion of the reservoir. To the east and north-east of the reservoir, respectively, are two other geothermal projects which serve to provide heat mainly to greenhouses, highlighting the proximity and potential of interaction of geothermal projects. The two wells have been drilled vertically for some eight hundred metres, where they deviate from vertical and from each other, so that water can be pumped between them over a horizontal distance of around 1.3km at reservoir depth. Hot water will be produced at around 80°C initially at a rate of up to 350m$^3$ per hour and after thermal energy is extracted will be re-injected at a temperature as low as 20°C. This leads to a maximum thermal energy extraction rate of ~25MWth.

The heat-supply aims of the project to supply an existing second-generation heating network on the TU Delft campus and a newly constructed heating network supplying existing buildings in a part of the city of Delft, the Netherlands. The TU Delft campus heating network currently operates at a ~110-130°C supply temperature, which will be modified to operate at a reduced temperature, i.e. ~80°C or less for the majority of the year/weather conditions, and elevated to ~90°C via a heat pump when the outside air temperature drops below -10°C via a heat pump, i.e. turning it into a third generation heating network. This heating network will also be expanded from four tracks to five to supply further existing buildings associated with the campus. The newly constructed heating network (called Open Warmtenet Delft https://www.delft.nl/warmtenet) will supply a portion of high-intensity housing in the city built in the 1960s and 1970s. A novel high-temperature aquifer thermal energy storage (HT-ATES) system is planned to be installed to bridge the seasonal fluctuation in heating demand (Bloemendal et al., 2020), and an above ground buffer tank is planned to provide a daily buffer. Additional peak capacity, when needed, will be provided by the existing gas-fired boilers which currently supply the heating requirements of the TU Delft campus. Due to the combined capacity of the geothermal doublet, the HT-ATES, heat pump and short-term buffer it is anticipated that ~95% of the thermal energy can be provided.

During the second half of 2023, both wells of the doublet have been installed, alongside a substantial scientific data and sample collection programme. To install a functional injector well, a side-track was required from ~830m to final depth at ~2.5km due to wellbore instability, and a second side-track at ~2.2km depth (see Figure 2), which slightly reduced the doublet spacing. The research questions that are targeted to be answered relate to field-scale geothermal operations, e.g. How reliable is the long-term energy production? How do materials perform in the long-term? and How can geothermal projects be best monitored?

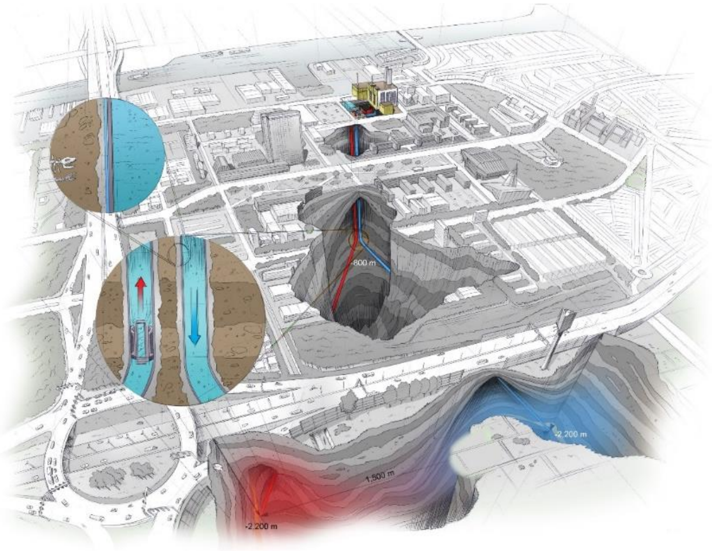


***Figure 1:*** *Illustration of the Geothermie Delft geothermal doublet, demonstrating the deviated wells and the TU Delft campus (illustration credit: Total shot productions).*

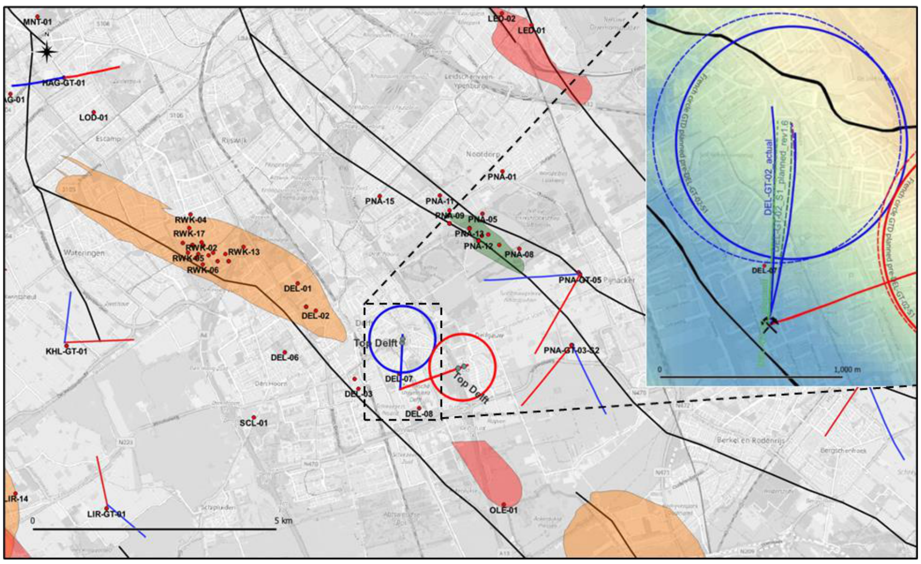


***Figure 2:*** *Map indicating the project location (wells and approximate influence area indicated by the red and blue lines and circles near the center of the figure), the surface surrounding the project, the main subsurface faults, offset wells and oil and gas fields. Inset: details of the initial injector wellbore on the left and the side-tracks on the right of the initial bore. (credit: Annelies Bender and Walter Eikelenboom, Aardyn)*

## 3. SCIENTIFIC PROGRAM

One of the key project aims is to install measurement instruments and collect samples and data in order to address the scientific questions listed above. For more information on the wider scope, this website has up-to-date information: https://tudelft.nl/geothermalwell. For the initial part of the program, solid sampling, wireline logging, fiber optic installation and installation of a local seismic monitoring system were undertaken. Drilling and well parameters were made available by the operator to the research team. In the following research program, an HT-ATES system will be installed, a deep observation borehole is planned directly through the cold plume, extending significantly below the reservoir, tracers will be utilized and a bypass system installed so that experiments can be undertaken live on the produced geothermal brine.

Rock samples were taken using a variety of methods, selected due to speed, cost, being intact and having a comprehensive set of samples, with a summary of the collected samples presented in Table 1. Cuttings were sampled throughout the drilling at a resolution of between 3 m and 10 m depending on the relevance to the scientific questions and the drilling speed, with a total of over 2000 samples taken. Cores were split across the two wells, with a focus on the cap-rock and the reservoir. 4” cores were taken in the producer (DEL-GT-01), in the cap-rock and the upper reservoir capturing a sample of the alternating shale / sandstone reservoir section typical of the fluvial origin of the reservoir. The coring operation proved challenging, due to the inclined well-bore, and highly heterogenous formation which resulted in core-jamming during the operations, restricting the length of core recovery for each coring run. A total of ~86 m were recovered, with 70 m in a continuous sequence. In the injector (DEL-GT-02-S2), a total of 81 side-wall cores were collected, which allowed sampling throughout the reservoir and targeting of key features within the reservoir, as this was done after wireline logging. Prior to any physical or destructive testing on the cores, the cores have been preserved in as intact a manner as possible. For this purpose, the cores were stabilized within their barrels by injecting foam, and sealing the cores with a wax and a vacuum pack comprising aluminum and plastic layers to reduce water and oxygen leaving or entering the cores. Shale cores were additionally stored in a fridge to reduce drying. Core plugs will be taken from the ends of select cores, to allow initial investigation, after which the cores can be again re-sealed. Electronic cores (via CT scanning) have been made of all the cores and further detailed scanning may take place before deciding which tests can be done on each core.

A comprehensive wireline logging campaign was undertaken in each well in the reservoir section. This included the following logs: Gamma Ray, Spectral Gamma Ray, Caliper, Bulk Density, Neutron Porosity, Micro-Resistivity Image, Dipole Sonic (including full wave form), Ultra-Sonic Borehole image and Nuclear Magnetic Resonance. In addition, the sonic logs were also run within cased hole to provide information on the cementation of those casings. An example of a selection of the data is shown in Figure 3 over a ~100m depth range. The heterogeneity of alternating sand and clay layers, corresponding properties and geological features can be clearly observed. These are expected to lead to a complex heat transfer behavior during project operation, and this will be a focus of ongoing research.

*Table 1: Samples collected during doublet installation (depths are in Measured Depth (MD), i.e. length along the well).*

| Well | Sample Type | Amount | Top Depth (m MD) | Bottom Depth (m MD) | Sampling rate |
|---|---|---|---|---|---|
| **Producer DEL-GT-01** | | | | | |
| | Cuttings | 1083 | 90 | 2930 | |
| | | 154<br>632<br>297 | 90<br>845<br>2511 | 840<br>2510<br>2930 | 10 m<br>5 m<br>3 m |
| | Core | 85.58 m | 2511.5 | 2651 | |
| | Brine | 11 | Mixed from reservoir | | |
| **Injector (motherbore) DEL-GT-02** | | | | | |
| | Cuttings | 729 | 90 | 2638 | |
| | | 152<br>461<br>116 | 90<br>845<br>2293 | 840<br>2290<br>2638 | 10 m<br>5 m<br>3 m |
| **Injector (side-track 1) DEL-GT-02-S1** | | | | | |
| | Cuttings | 132 | 2000 | 2560 | |
| | | 45<br>87 | 2000<br>2303 | 2300<br>2560 | 5 m<br>3 m |
| **Injector (side-track 2) DEL-GT-02-S2** | | | | | |
| | Cuttings | 123 | 2218 | 2581 | 3 m |
| | Sidewall Core | 81 | 2349.8 | 2556.1 | |

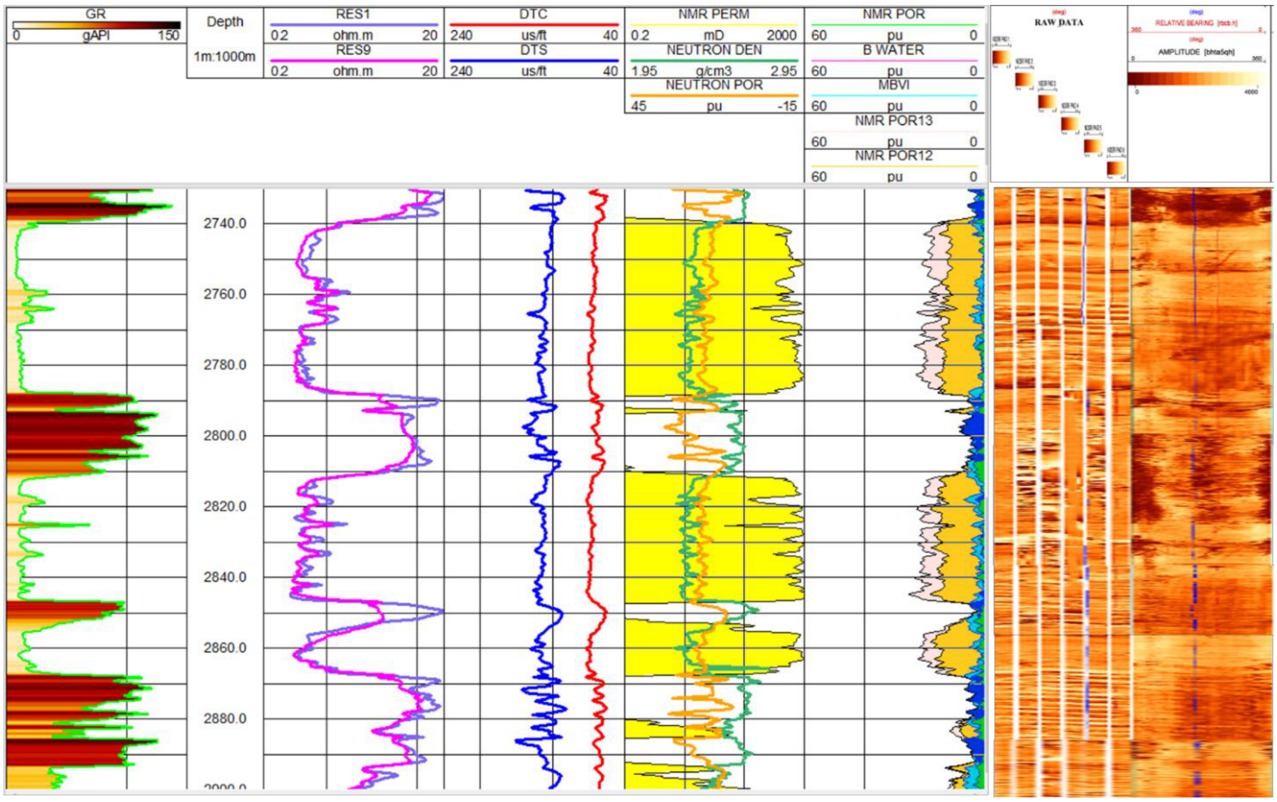


***Figure 3:*** *Sample of the wireline logging data for the producer well at the reservoir depth along the well path (meters in measured depth, i.e. the along-well depth). Logs from left to right: GR=Gamma Ray; RES=Resistivity; Sonic, DTC=compressional wave slowness, DTS=shear wave slowness; Neutron density and porosity; NMR=Nuclear Magnetic Resonance; Micro-Resistivity and Ultra-Sonic Imagers.*

A fiber optic cable is being produced at present which will be installed inside the production well casing during commissioning. This cable is being designed to have distributed pressure, temperature and acoustic sensing, which will allow dynamic and continuous well testing during operations, and is designed to investigate the short- and long-term influence of the reservoir heterogeneity. In addition, a longer-term plan is to install a monitoring borehole within the cold plume, in order to monitor the temporal and spatial distribution of the injected cold water.

The area where the geothermal project is installed is not naturally seismic (Muntendam-Bos et al., 2022), and does not have previously observed seismic activity. However, there is a significant social focus on seismicity and current models predict the potential of seismicity from cooling (Buijze et al., 2021), despite only a single M0.0 seismic event being measured due to comparable geothermal projects in the Netherlands. Therefore, a local seismic network surrounding the project has been installed, with the layout shown in Figure 4. The system was designed in order to be able to detect and locate any seismic activity related to project activities. The centreal and two most southerly seismic stations were installed to 200m depth. At the top of the figure, the northern seismic monitoring station DAPGEO-02 is seen, which was developed as a significant sub-project (Vardon et al., 2023). Here, a 500m deep seismic monitoring station was installed. A series of geophones and optical fibres were installed to investigate low-magnitude seismicity and to calibrate downhole fibre-optic equipment to be installed in the wells. A coring programme was undertaken in sand formations potentially suitable for (high-temperature) thermal energy storage and deep clays suitable for use as a caprock for thermal energy storage and at representative geological conditions for the disposal of radioactive waste (note: no radioactive waste disposal will take place in this location). In addition, a comprehensive logging suite was taken including Nuclear Magnetic Resonance, density and shear-wave velocity logging, which are rarely taken in the shallow subsurface.


***Figure 4:*** *Layout of the local seismic geophone network (orientation such that north is vertical)*

To ensure that the data can be combined and assimilated with geological and reservoir modelling techniques, a digital twin is being established. The objective is to integrate all data, models and geological interpretations, with the objective to improve decision making in future geothermal projects (Voskov et al., 2024), especially in locations where multiple projects may interfere with each other or have the opportunity to be operated as a field.

## 4. SCIENTIFIC DATA AND AVAILABILITY

All data is targeted to be collated and released publicly. The data strategy is illustrated in Figure 5, where raw data will be made available augmented by metadata and industry standard formatting and stored on a data repository with a fixed digital object identifier (DOI), which ensures that the data is unchanged and maintained. The project DOI is: https://doi.org/10.4121/85b3725b-80fa-4b0b-9db2-475bfd8f0265. Data derivatives, i.e. raw data after processing, analysis, modelling or data compiled for article publication will be separately stored, including citation to the raw data, and will have their own DOI. This is designed to ensure traceability and availability of the data. These data will also be included in the EPOS data portal (https://www.epos-eu.org/dataportal) which is designed to catalogue and bring together solid earth science data in Europe and will improve the findability and accessibility of the data.

At present the data collected during the drilling of the doublet is being prepared for upload onto the data repository. The first dataset will be the wireline logs which will be available this DOI: https://doi.org/10.4121/2a7b2a63-dd7b-46bc-a275-97729b3ab348. To allow the researchers involved in designing and executing the data collection to make first use of the data, a two-year embargo on data may be implemented at their request. However, when possible, data will be made public earlier and metadata will always be available, so that available data when under embargo can be personally requested.

The data which were collected during the drilling of the seismic monitoring borehole (DAPGEO-02, see Figure 4), is findable via the overall project DOI, but also available separately: Drilling Report https://doi.org/10.4121/21640148.v3, Initial borehole dataset https://doi.org/10.4121/20299644.v2 and Core CT-scans https://doi.org/10.4121/21528819.v2.

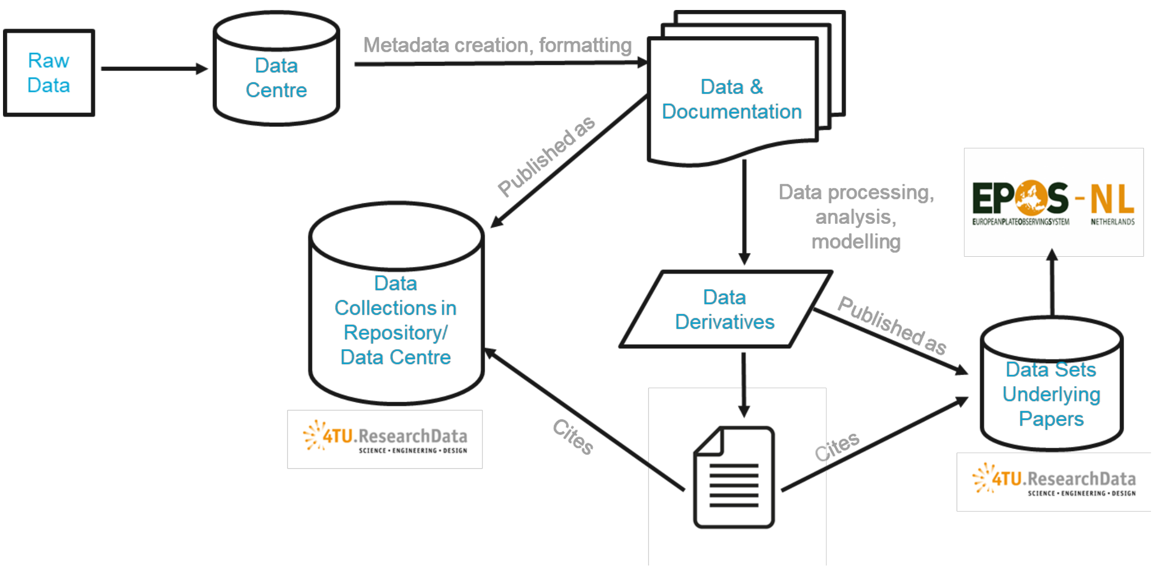


***Figure 5:** Data curation approach.*

## 5. CONCLUSIONS

A geothermal doublet with a joint scientific and energy production aim has been recently drilled on the TU Delft campus. This project was designed to encompass scientific infrastructure and therefore offers an opportunity for detailed scientific study on a low-enthalpy geothermal project in a heterogeneous sedimentary fluvial reservoir. The doublet will be integrated into a heating network, comprising two heating networks, an aquifer thermal energy storage system, a local buffer and a large heat pump, with the intention of supplying energy with virtually zero associated carbon emissions. An overview is presented of the currently installed equipment and the samples taken, with the data curation approach detailed, with the objective of creating a lasting reference geothermal project.

## ACKNOWLEDGEMENTS

We would like to acknowledge the team effort that went into this project, from the initiators of the idea and those who developed it over many years, to the members of the Geothermie Delft consortium, stakeholders and supply chain, to the team of researchers involved, including many current students who worked as project assistants, sometimes overnight and frequently in the rain. In particular, we would like to thank Leendert-Jan Ursem and Bas Schravendijk from Aardyn, without whom the research and commercial aspects of the project could not have been combined. The commercial side of the project is funded via the Geothermie Delft consortium, and the main funding for the research activities comes from NWO via the EPOS-NL project and from the university.

## DATA AVAILABILITY

We believe in open science. All data collected by the research team will be available when it has been prepared for dissemination. Much is available on the 4TU research repository with a collection DOI of https://doi.org/10.4121/85b3725b-80fa-4b0b-9db2-475bfd8f0265. For a discussion on access to other data, please contact our data manager Liliana Vargas Meleza (geothermal@tudelft.nl). Access to samples may also be possible. As samples may be destroyed by their use, a committee has been set up to assess access requests. Please contact us for further information.

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# NATURE BASED SOLUTIONS – OVERCOMING THE CHALLENGES OF COLLECTING RELIABLE BASELINE DATA IN REMOTE ENVIRONMENTS

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## ABSTRACT

*Nature-based solutions require realistic targets, ideally based on processes operating in intact ecosystems. Due to widespread human impacts, the least disturbed ecosystems in Ireland often occur in remote settings, make characterising natural processes challenging. Difficulties associated with accessing these areas requires an alternative approach to water sampling, particularly when there is a need to characterise processes that occur during high energy hydrological events. Remote telecommunications, automated samplers and sensors help meet this requirement. However, telecommunications often prove problematic where remote connectivity is most needed. More recent developments in communications standards, including machine-to-machine (M2M) communications, have highlighted their potential, yet require further development. Similarly, although a number of vendors offer either complete or partial solutions for remotely-accessible sensor and autosampler equipment, finding packages that offer the appropriate combination of flexibility and accessibility for remote sites, with limited telecommunications potential, has proven difficult. The US-Ireland funded Sensor Application to Peatland Hydrology In Remote Environments (SAPHIRE) project has adopted a hybrid approach, selecting a platform with independent power supplies, the autonomy to integrate existing institution-owned equipment and the flexibility to utilise Internet of Things (IoT) communications standards, in combination with a highly flexible cloud computing platform. Data collected thus far have demonstrated the viability of this approach for detecting flood events and remotely activating automated water sample collection. The approach adopted permits the programme to continue to develop sensor and sampling protocols to better quantify the ecosystem services that underpin nature-based solutions to water-related issues.*

**Key words:** *Peatland, Hydrology, Sensor, Telecommunication, Internet of Things (IoT), Machine-to-machine (M2M).*

## INTRODUCTION

### BACKGROUND

Healthy habitats can provide valuable ecosystem services underpinning nature-based solutions needed for sustainable environmental quality. Restoration of degraded ecosystems, although widely promoted, requires realistic quantifiable objectives, ideally based on intact habitats. This requires data collection from these intact habitats to inform restoration activities.

Water is a fundamental abiotic component of aquatic and wetland ecosystems. Measurement of physical and chemical aspects of the hydrological cycle at fixed points, coupled with relevant spatial data, forms a key element for characterising processes, including flow and water level regimes and pathways for delivering water to rivers, streams and lakes. Field data generated from areas with these habitats, provide essential underpinning for modelling efforts to quantify deviations from natural conditions, and how these impact natural processes supporting nature-based solutions.

CHALLENGES

Hydrological processes operate over a range of temporal scales, with those operating over short times, although being potentially significant, are particularly challenging to characterise. Recent technological advances have facilitated collection and storage of high frequency, long term measurement of key parameters, such as rainfall/evapotranspiration, groundwater levels and stream stage, to better underpin key physical elements of catchment water balances. In a similar vein, comparable technology can be applied to useful water quality parameters, including temperature and electrical conductivity, which allow key parameters, such as specific electrical conductance (SEC) to be calculated and used as surrogates for laboratory analytes, following calibration. Furthermore, combination of flow and concentration data may be combined to calculate water quality parameter loads and fluxes (where contributing areas are known).

Despite these advances, considerable data gaps remain, particularly in determining stream loads and fluxes. Apart from requiring laboratory analyses to calibrate water quality sensors, many parameters cannot be measured in situ and lack suitable field-based surrogates. Under these circumstances collection of water samples for laboratory analysis proves necessary. Although routine grab sample collection can prove useful, large sample numbers are usually required to fully characterise systems. This can prove financially prohibitive and logistically prolonged, while also potentially containing large levels of redundancy in the resulting dataset.

By contrast event-based sampling provides a means of collecting focused data, often reflecting a range of hydrological processes, and typically with less redundancy. However, sampling in this way poses a number of logistical challenges, even when using automated sampling devices (autosamplers). Critically, initiating sampling can prove problematic. Although sensors may be employed (individually or in combination) to identify event thresholds, baseline conditions and parameter changes during transition to hydrological peak, as demonstrated in Figure 1, can be missed by autosamplers activating on stage/ discharge/precipitation. Furthermore, knowing whether autosamplers have activated relies on the presence of a reliable communications system.

## US-IRELAND SAPHIRE PROGRAMME

Recent technological developments, most notably in the area of telecommunications, have aided significantly in implementing event-based sampling. Wireless communication now allows key physical hydrological elements, such as rainfall, and water level, to be observed remotely, while comparable technology facilitates sampler activation and sensor sampling frequency adjustment.

The technological developments outlined display considerable potential for data collection to better understand hydrological conditions in wetland and aquatic habitats. This proves particularly the case for characterising undisturbed/near-intact habitats, which typically occur in remote settings that are difficult to access, while in many cases, displaying rapid responses to rainfall. Although communications in these areas previously proved challenging, with satellite based telemetry proving necessary for remote settings, the continued development of mobile phone and internet of things (IoT) technology has facilitated application of lower cost communications technologies. Many of these have been developed by commercial vendors, yet have the disadvantages of often being restricted to a vendor's devices, while also incurring significant costs and operational overheads.

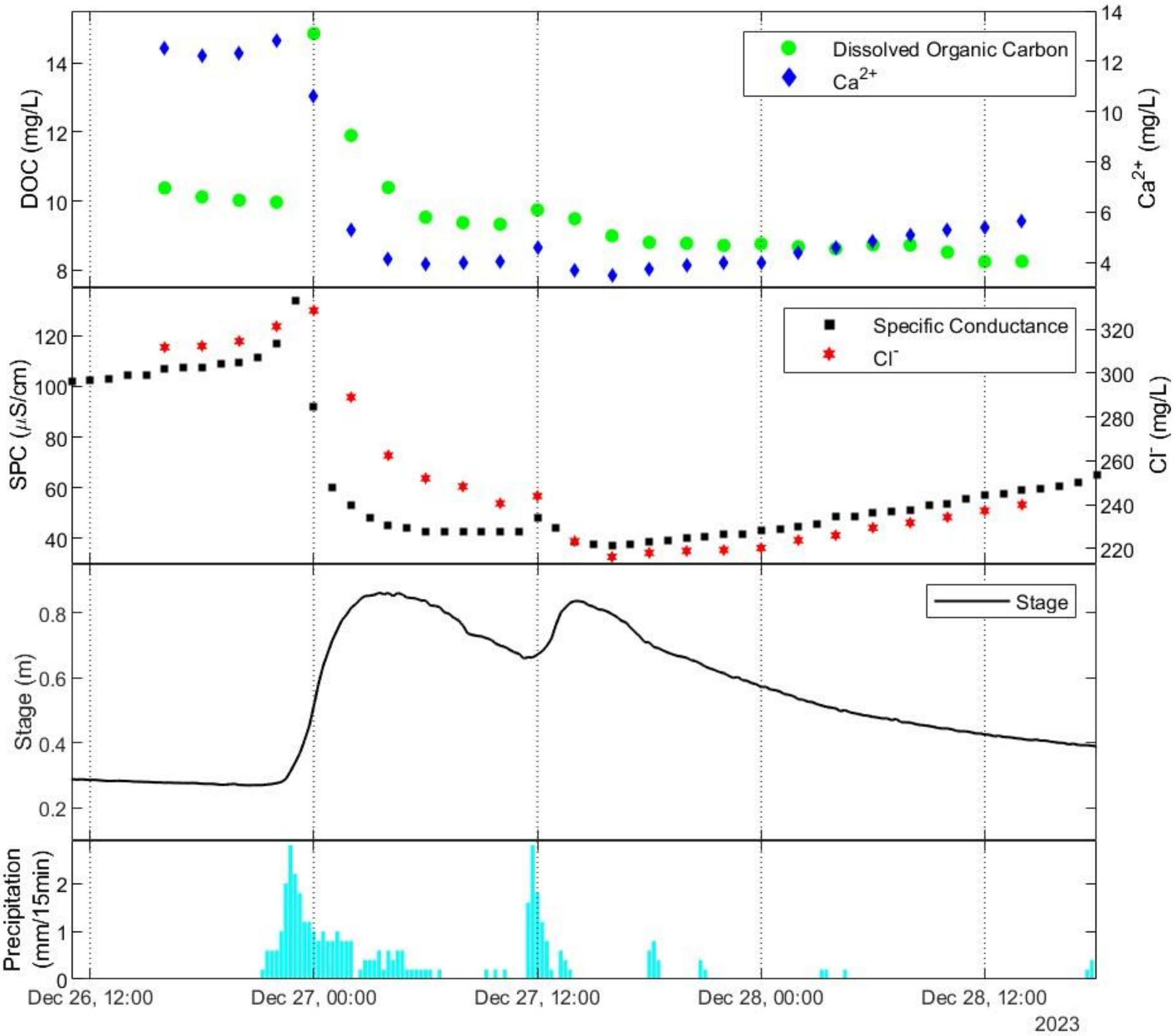



***Figure 1:*** *Subset of Letterunshin surface water and meteorological data, obtained through continuous high frequency sensor measurements (specific conductance, stage, precipitation) and laboratory analysis of remotely-activated, automated 2-hourly sample collection ($Cl^-$, dissolved organic carbon, $Ca^{2+}$).*

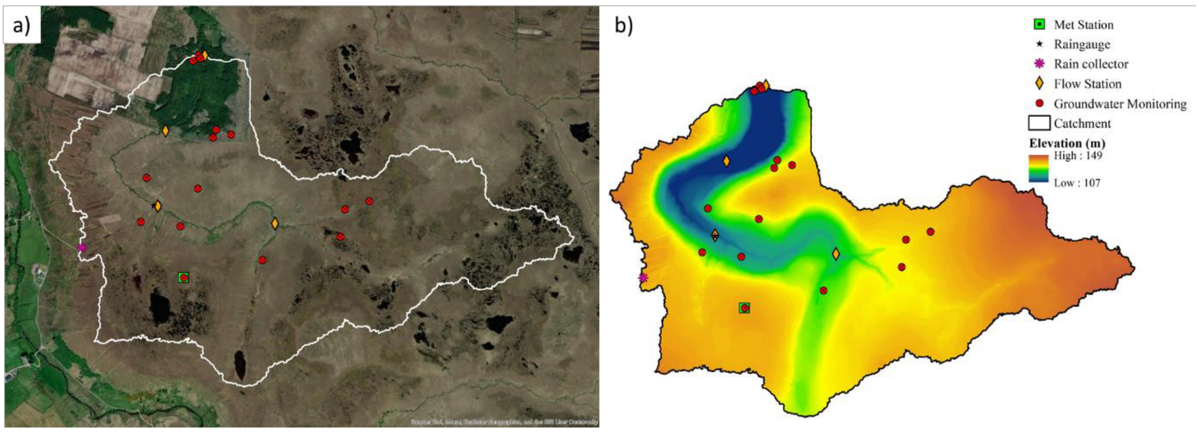
The US-Ireland funded Sensor Application to Peatland Hydrology in Remote Environments (SAPHIRE) aims to widen the use of remote observation/data collection of hydrological data in isolated settings using existing low cost technologies, while also proving sufficiently versatile to incorporate additional sensors, from multiple suppliers, that allow measurement of new parameters. The resulting technologies need to be sufficiently robust to withstand harsh environmental conditions, while reliably measuring key physical and water quality parameters at sufficient frequency to characterise environmental conditions across remote sites. At the same time the technologies employed need to enable 24/7 communications to both activate and download devices. This presentation will outline the technological choices and selection rationale made by SAPHIRE, to achieve an improved understanding/quantification of physical hydrological processes and water quality, in a remote near-intact Irish blanket peat-covered catchment.

## FIELD STUDY AREA

The Letterunshin Blanket Bog Hydrological Research Catchment (Letterunshin) is located approximately 7km to the southwest of Dromore West Co. Sligo in the foothills of the Ox Mountains. The area contains one the largest remaining relatively intact blanket peat-covered catchments on the island of Ireland, drained by the Fiddanduff River. Catchment topography is dominated by a flat plateau containing blanket bog/bog pool complexes, incised up to 30m by the Fiddanduff, in a valley which widens moving downstream (Map 1). Flynn et al. (2021) provides further details of the area. Briefly, the area of relatively intact peat, drained by the river, measures 1.6 km$^2$. This occurs immediately upstream of an area of 33ha overgrazed and partially drained peatland which also discharges to the Fiddanduff before it passes downstream into a 20ha subcatchment of clear cut plantation forestry (cut in 2022).

To evaluate the impact of land use on peatland hydrology and hydrogeology, a network of groundwater monitoring points, placed at seven locations on the undrained relatively intact catchment, two locations on the degraded catchment and four locations in the formerly afforested catchment, aimed to reflect representative groundwater regimes in contrasting physical/hydrological settings. As there was no requirement for live interaction with the data, self-logging sensors and a download routine were deemed sufficient.

Four flumes, located at the stream headwaters permit continuous monitoring of stream discharge. Autosamplers installed beside each flume permit intermittent collection of water samples, while water quality loggers measure temperature, conductivity, stage and stream flow measurements.




***Map 1:*** *Map of Letterunshin Blanket Bog Hydrological Research Catchment annotated with SAPHIRE hydrometric instrumentation: a) Landcover map, and b) Digital elevation map.*

An automatic weather station measures rainfall and parameters needed for calculation of potential evapotranspiration, while a second rain gauge, located at a lower elevation allows assessment of precipitation variability across the catchment. The data collected during the research programme build upon those collected during a previous EPA-Funded (QUBBES) project, initiated in 2017, employing much of the existing instrumentation, having a demonstrated track record.

INSTRUMENTATION ISSUES

As SAPHIRE required utilisation of existing sensors and equipment in addition to new data procurement options, it was essential that the sensor and communication system design offered the ability to integrate devices from multiple manufacturers, while remaining sufficiently flexible for further development throughout the project lifecycle. Although some platforms exist with this capacity, the software employed is not always transparent, making adaptation challenging to impossible and costly, often requiring manufacturer service support to make changes.

Moreover, this issue also applies to communicating sensor responses in order to facilitate remote access. Commercial systems with existing capacity prove expensive (>£5000-£9000), and often tie users into an external online data platform whose communications protocols are also not always clearly defined; this makes assessment of potential operational performance challenging.

SAPHIRE's first phase has focused on surface water. Letterunshin's remote location and topography resulted in poor cellular reception at flow gauging sites. When the potential for remote communications was assessed at the start of 2017, costly satellite communication packages were considered to be the only viable alternative. Since then mobile phone coverage and signal quality have improved across Ireland, and in early 2023, field testing across major telecommunications providers yielded signal strengths ranging from 'Poor' to 'Good', suggesting improved cellular communications, yet still leaning toward poor and intermittent service, particularly when restricted to a single network, using a standard data SIM. This prompted investigation into low power wide area (LPWA) technologies. Designed for the internet of things (IoT). LPWA enables long range and high penetration connectivity, thereby improving reliability for machine-to-machine (M2M) communications that transmit with low data requirements, such as those employed at Letterunshin.

Despite initial success trialling long range wide area network (LoRaWAN®) as an LPWA option, the lack of a LoRaWAN® gateway limited its wider application; the nearest existing available gateway (via The Things Network) was located, approximately three times the maximum operating distance away from Letterunshin. Moreover, while it is possible to deploy a private/community LoRaWAN® gateway anywhere, it requires a connection to the wider network, which in the case of Letterunshin, reverted back to reliance on the cellular network owing to the lack of suitable facilities in the area. Additionally, LoRaWAN®'s use of licence-free frequency bands, while making running costs inexpensive, leaves the system susceptible to interference; in the case of public and community networks, poor network management can lead to exceedance of available channels and consequently, further interference, data loss or enforced data restriction.

Furthermore, some cellular network operators have adopted LPWA standards to facilitate IoT communications, primarily through two standards, LTE-M and NB-IoT, which have the added benefit of using licenced frequency bands, yet offering a high quality of service through stringent network management. Critically, acquisition of operation and IoT SIM packages employing these approaches, via major network operators, proved highly challenging. Eventually, a major network NB-IoT SIM was sourced through a third-party provider and, whilst field testing was successful, limitations on the modem that could operate with this SIM, and its suitability for integration with existing equipment, discouraged selection of this standard. The aspiration to use LPWA and IoT technologies continues to prove elusive.

Aside from communications issues, the need to use reliable power sources in adverse environments (low temperatures, short periods of daylight) posed further problems. Given the sites location, routine changing of batteries (including for devices such as autosamplers) proves problematic. Costs of solar panels in 2017 proved prohibitive. Moreover, historical problems with livestock damage, coupled with high windspeeds, made the use of larger structures visually intrusive. On the other hand, the site's remote location made the possibility of human interference/vandalism remote.

## SOLUTIONS

To date the SAPHIRE project has focused on the development of systems to allow provision of data to identify the onset (and impending onset) of energetic hydrological conditions, and to facilitate event-based sampling at Letterunshin's four flumes. To this end the team instrumented each flow gauging site with an independent sensor network, underpinned by a reputable commercial off-the-shelf multichannel datalogger and modem, selected for provision of common sensor protocols (e.g., SDI-12, PakBus, Digital Control Ports, Pulse Counter) and autonomy of programming and configuration (Figure 2). The ability to self-write the datalogger code resulted in considerable savings in time and expense over commercial systems, while providing the capacity to add additional sensors as they become available. Moreover, the approach adopted permitted activation of autosamplers by remote configuration of datalogger variables (via MQTT).

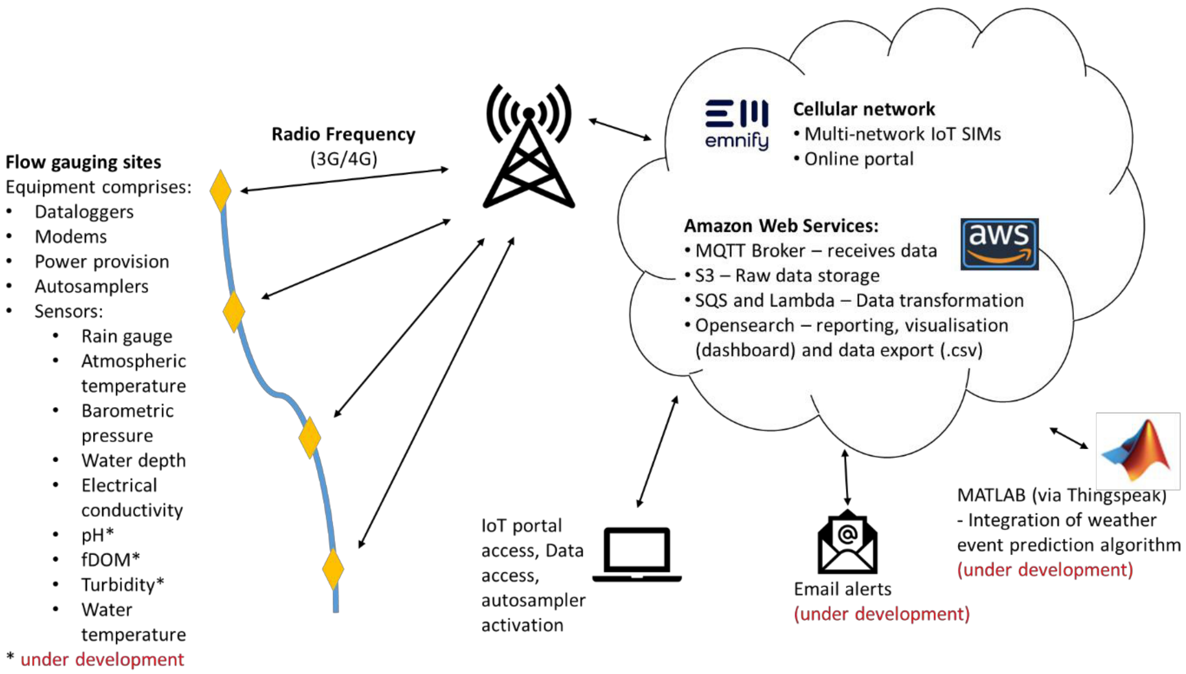



***Figure 2:*** *Schematic demonstrating sensors and network architecture employed by the SAPHIRE project in Letterunshin.*

Relative to 2017, when Lettersunhin was first instrumented, the cost of solar technologies has declined significantly in recent years. This has permitted the use of 120W solar panels, coupled with a 20Ah battery at each monitoring location. Monitoring over winter 2023 revealed that even during short days, displaying low levels of solar intensity, this approach operated satisfactorily. On the other hand, issues relating to adverse weather conditions and livestock hazard persist and led to installation of bespoke frames and fencing to protect against high wind speeds and livestock damage (respectively).

The communications solution has been successful though a combination of factors. Despite mobile phone signals proving largely satisfactory, installation of high gain (8dBi) antennas ensured best possible performance under low signal strength. Use of a multi-standard/multi-network IoT SIM (2G,3G,4G,5G, NB-IoT and LTE-M) optimised re-establishment of connectivity to the strongest available network and standard. While selected modem capabilities were restricted to 2G/3G/4G, the IoT SIM provided additional features that would otherwise be unavailable with a standard SIM. These included an online portal to allow visibility of network connectivity, data activity, and cost. Crucially, this approach provided private static internet protocol (IP) addressing and virtual private network (VPN) access, to enable direct communication with remote devices to allow fault-resolution when required. (Complementary to the IoT SIM is the selection of MQTT as a lightweight M2M IoT standard, reducing network bandwidth requirements and consequently providing greater reliability under low network signal strength and lower data costs over more conventional standards.)

Adopting this technology required generation of a dedicated communications protocol. Amazon Web Services (AWS) was selected as a cloud computing platform, as it could facilitate MQTT messaging, and process received data for long term storage, export and dashboard visualization. AWS also has the capacity for further development of live data analysis using machine learning algorithms, thus enabling automated autosampler activation, prior to the onset of energetic hydrological conditions based on meteorological data, currently under development by the project. Whilst AWS offers tutorials and documentation on system operation, engagement of an AWS-Certified third-party expert for initial configuration proved cost effective ($350).

PERFORMANCE

Following a programme of testing and field validation, the setup developed by SAPHIRE now meets technical goals, allowing remote access to high quality (resolution/frequency) hydrological data, while also facilitating remote activation/deactivation of autosamplers.

Despite using high end data loggers, the development of an alternative sensor network and communication platform has proven inexpensive yet sufficiently versatile to facilitate event-based sampling (Figure 1). Moreover, the availability of additional channels facilitates the expansion of sensors for further water quality surrogates, e.g., for aqueous organic carbon. From a cost perspective, Tables 1 and 2 compare hardware and operational costs against those for commercial models/platforms. Hardware costs are limited to the key equipment required to integrate with existing sensors and do not include ancillary items such as cables, antennas, power supplies, etc. It is important to note that there can be significant variability in these costs; some vendor's equipment can only integrate with their own proprietary ancillary equipment. This knowledge was also instrumental in the choices made by SAPHIRE. From the information presented, it is clear that considerable savings are possible, while autonomous configuration capability displays potential to make the approach adopted even more economic.

Billing associated with the communications protocol adopted is constructed in a usage-based tier system. The majority of SAPHIRE's functions fall within the free-tier for the first 12 months, and as such, year 1 costs are ~$3/month. This is anticipated to increase to a maximum of $35/month in year 2 and beyond.

***Table 1:*** *Comparitive Hardware costs (approximate, for four devices)*

| Hardware type | Vendor A | Vendor B | SAPHIRE |
|---|---|---|---|
| Datalogger | €16,600 | €8,400 | €6,800 |
| Modem | Cost unknown | Integrated with datalogger | Integrated with datalogger |
| Software | €2850/licence | Not required | included |

***Table 2:*** *Comparative Operating costs (approximate, for four devices)*

| Operational requirements | Vendor A | Vendor B | SAPHIRE |
|---|---|---|---|
| Data SIM | To be self-sourced | €240/yr | €80/yr |
| Online portal | Not specified | €420/yr | <€400/yr (<€35/yr, year1 only) |
| Configuration changes | Unknown | Unknown | €0 |

## PROBLEMS AND PERSPECTIVES

The challenges faced by SAPHIRE researchers, although not atypical for many environmental professionals, are infrequently encountered more widely. This has resulted in the reliance on specialised equipment and software, which may prove inappropriately adapted for the task(s) at hand and may require compromises in its use. Moreover, high costs, coupled with less than ideal communication protocols have often made collection of relevant hydrological and hydrogeological data at suitable frequencies highly challenging. The SAPHIRE programme aimed to address this and in doing so make collection of appropriate data more amenable to environmental professionals.

Progress to date on the programme has assisted in achieving this goal (See Figure 1). Real time monitoring of hydrological processes, coupled with high frequency device activation and data downloads now make key challenges, such as focused event-based sampling, feasible, even in isolated settings. This has led to an improved understanding of peatland hydrology and the role played by groundwater, while also revealing further data needs upon which, future acquisition efforts need to focus.

Some of the data collected has called into question some widely held assumptions. Despite peatlands being promoted as sponge-like bodies, capable of absorbing and releasing significant quantities of water from storage, groundwater records reveal water tables occur persistently close to the ground surface, reflecting limited available storage capacity. This gives rise to flashy stream flow regimes, even immediately following prolonged dry periods. More generally even relatively intact blanket peatlands have flashier flow regimes than originally anticipated. This has led to flumes drowning out, particularly near the Fiddanduff River's headwaters. Comparable conditions occur at other locations, albeit less frequently.

Although the stage data collected in the hydrometric network remain reliable, routine over topping of flumes requires them to be rated for high flows. Approaches are currently being developed, using existing devices and the technologies and protocols generated during the SAPHIRE project, with the intention of applying the solution to other unrated structures. This approach will require improved system portability, which is currently undergoing development.

More generally, findings have implications beyond peatland hydrology, with the reduced monitoring and communications costs making sentinel/emergency alert systems for flooding/ pollution events in both groundwater and surface water systems more affordable and accessible to a wider range of users. As a corollary to this point, provision of key hydrological and water quality data serves to allow environmental professionals to characterise abiotic ecosystem elements and associate ecosystem services with greater confidence.

## ACKNOWLEDGEMENTS

Sensor Application to Peatland Hydrology in Remote Environments (SAPHIRE) project is supported by the USI 177 research grant from the Department for the Economy, Northern Ireland under the US-Ireland R&D Partnership Programme, the U.S. National Science Foundation GEO EAR 2114028, and Science Foundation Ireland (21/US/3724).

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# SESSION V

# PEATLAND RESTORATION - ONGOING RESEACH

**Laurence Gill,** *Trinity College Dublin, Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin 2, Ireland*

## ABSTRACT

*This paper describes research carried out into the ecohydrology of raised bogs in the midlands of Ireland by the TCD Environmental; Engineering group over the past few years and how it leads into the ongoing research on the extensive restoration of peatlands being carried out by Bord na Mona. Five different bogs are currently being monitored to assess the success of the engineering works that have been carried out, aimed at rewetting the areas to promote the growth of peat forming Sphagnum.*

**Key words:** *raised bog, restoration, rewetting, wetlands.*

## BACKGROUND

Ireland's peatlands, occurring as raised bogs, blanket bogs or fens, host unique ecological communities, which contribute to global biodiversity, carbon regulation and other ecosystem services. However, exploitation has reduced the habitats' distribution and damaged their ecohydrological functioning. Mechanised commercial peat extraction, combined with marginal turf cutting, has resulted in the loss of >80% of the original raised bog area. As a result, despite peatlands covering over 20% of the Irish landscape, only 9% of the original raised bog area is considered to be suitable for conservation and less than 1% of this area is actively forming peat (NPWS, 2018). Peatland restoration and rehabilitation activity in Ireland has increased significantly over the past few years with large-scale projects such as Bord na Móna's PCAS scheme which aims to restore 33,000 hectares of their previously mined lands back to wetland ecosystems (DECC, 2021)

Since the late 1980s, raised bogs in Ireland have increasingly been the subject of research by scientists and engineers from Ireland, Britain and The Netherlands. This has led to an enhanced understanding of the ecology and the hydrological conditions necessary for their maintenance and restoration, including the development of ecotopes, vegetation communities that represent both the ecological condition and hydrological signature of the bog. The Environmental; Engineering group from Trinity College Dublin has been carrying out research on the ecohydrology of raised bogs in Ireland over the past few years, with much of the early research focused on Clara bog in County Offaly as one of the few raised bogs still functioning in a near natural condition. Other research projects then followed, investigating both the hydrology and carbon fluxes from other more degraded sites and sites under different levels of restoration. These have led to ongoing research on the extensive restoration of peatlands currently being carried out by Bord na Mona.

## PREVIOUS RESEARCH

### ECOHYDROLOGY

A number of ecotopes have been classified for raised bogs, with four primary ecotope types, namely marginal, submarginal, subcentral and central, being the most common and widely distributed. *Central* and *subcentral* are considered to be the Annex I-type active raised bog, *submarginal* constitutes degraded raised bogs, whilst *marginal* is damaged and is considered incapable of regeneration without significant human intervention. The ecohydrology of two raised bogs, Clara bog and Abbeyleix bog, was intensively studied over a two-year period (Regan *et al.*, 2020). Comprehensive hydrometric monitoring networks were installed at the bogs at different representative ecotope sites involving phreatic and piezometer tubes to monitor the groundwater head conditions in the peat and underlying till subsoil, as well as flumes at the main drainage outlets to monitor runoff. The results indicated that active raised bog occurs where water tables are within 100 mm of the ground surface for approximately 90% of a given year (see Figure 1). The studies also showed that the maintenance of high water levels in the peat may not just only be a function between the rainfall onto the bog and the hydraulic conductivity of the peat, but may also be linked to the hydraulic head in the underlying regional groundwater (Regan *et al.*, 2019).

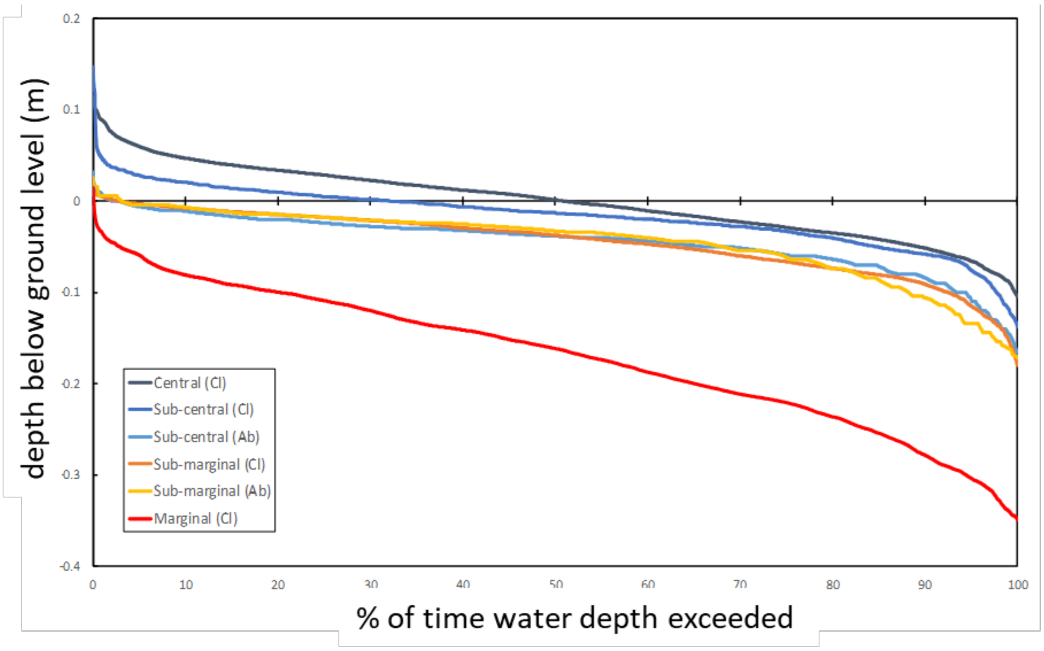


***Figure 1****: Water table duration curves for ecotopes at Clara and Abbeyleix (2015–2017) (Regan et al., 2020).*

To investigate the hydrological properties of the vegetative layer and near-surface peat, microcosm experiments were also carried out at Abbeyleix to quantify the storage properties of the different vegetative areas and the water input from shallow lateral flow (Swenson *et al.*, 2020). The results (see Figure 2) showed the importance of lateral flow in maintaining and restoring active raised bog conditions, by comparing the changes in storage inside and outside the microcosms. The timing and magnitude of the lateral flow differed considerably between locations with differing ecological conditions (i.e., different ecotopes), indicating that shallow lateral flow is an important determining factor in the ecohydrological trajectory of a recovering bog system. For locations where a *Sphagnum* spp. moss layer was present, a slow continuous net lateral input of water from the upstream catchment area supported the water table during drought periods, which was not observed in locations lacking *Sphagnum*.

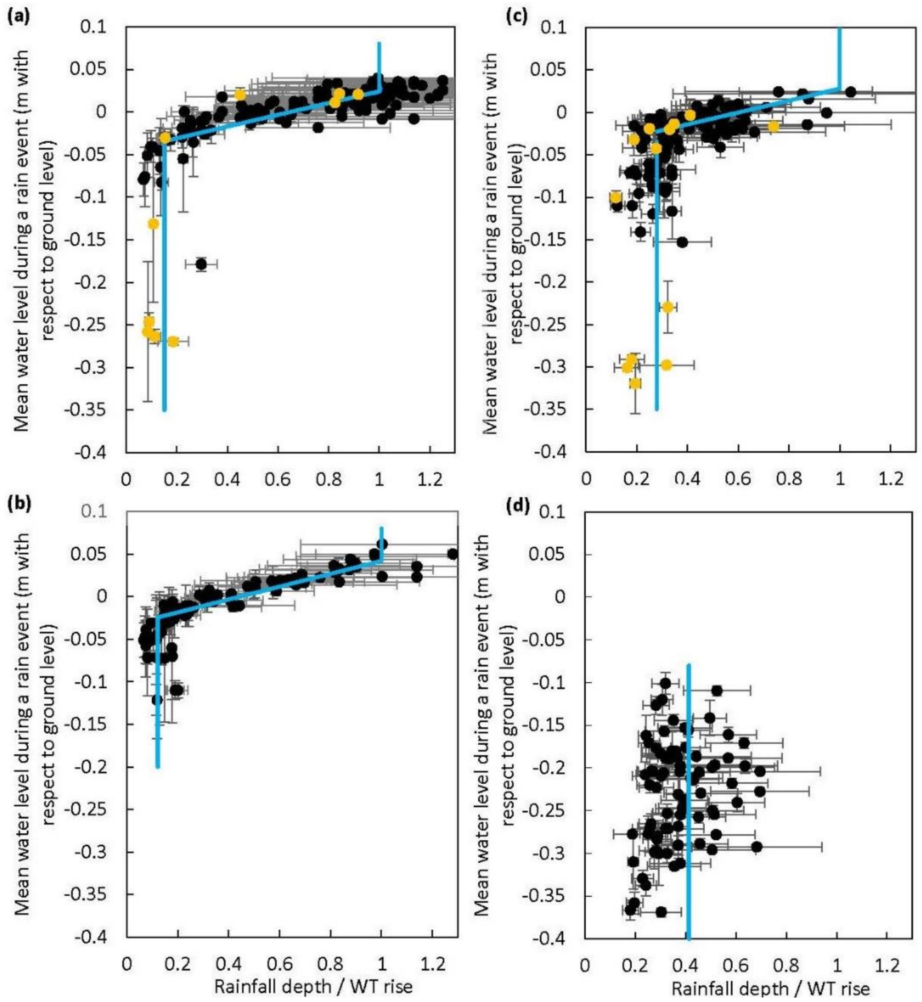


***Figure 2:*** *Storativity curves for (a) Eriophorum cutover, (b) sub-marginal, (c) sub-central and (d) Sphagnum cutover. The blue lines are the idealised storativity curves. The horizontal error bars are the error in the storativity based on the measurement limitations of the water table and rainfall. The vertical error bars represent the total change in the water table across a storm event.*

## CARBON FLUXES

There have been an increasing number of research projects in Ireland (and globally) trying to quantify gaseous carbon (carbon dioxide and methane) fluxes from different peatlands using either chamber methods at specific points or more integrated measurements using eddy flux covariance towers. These measurements of carbon dioxide compare the carbon accumulated by the vegetation in terms of gross primary productivity (GPP) against the carbon lost in terms of ecosystems respiration (ER) to yield the net balance, the so-called net ecosystem exchange (NEE). Research was carried out on $CO_2$ fluxes using chamber methods on Clara bog and Abbeyleix bog across different representative ecotope sites. The temporal variation over a two-year period between GPP and ER to yield the NEE for the different representative vegetation communities are shown for Abbeyleix on Figure 3 (and see Regan *et al.* (2020) for Clara bog), clearly; show the highest cumulative uptake in the healthy raised bog *Sphagnum* dominated ecotopes (central and sub-central) compared to net carbon losses in the areas with ecotopes more characteristic of drained bog conditions (i.e. the marginal / sub-marginal ecotopes and the *Calluna* and *Erioophorum* cutover sites). In order to assess the total carbon sequestration (or otherwise) for such bog ecosystems, gaseous losses due to methane and fluvial losses due to particulate and dissolved organic matter also need to be taken onto account, which is work just being completed as part of the EPA funded SMARTBOG project. In general, the results from this research and other being carried out in Ireland and more globally seem to indicate that a healthy raised bog in a temperate climate should uptake 30 to 60 g-C/m$^2$/yr.

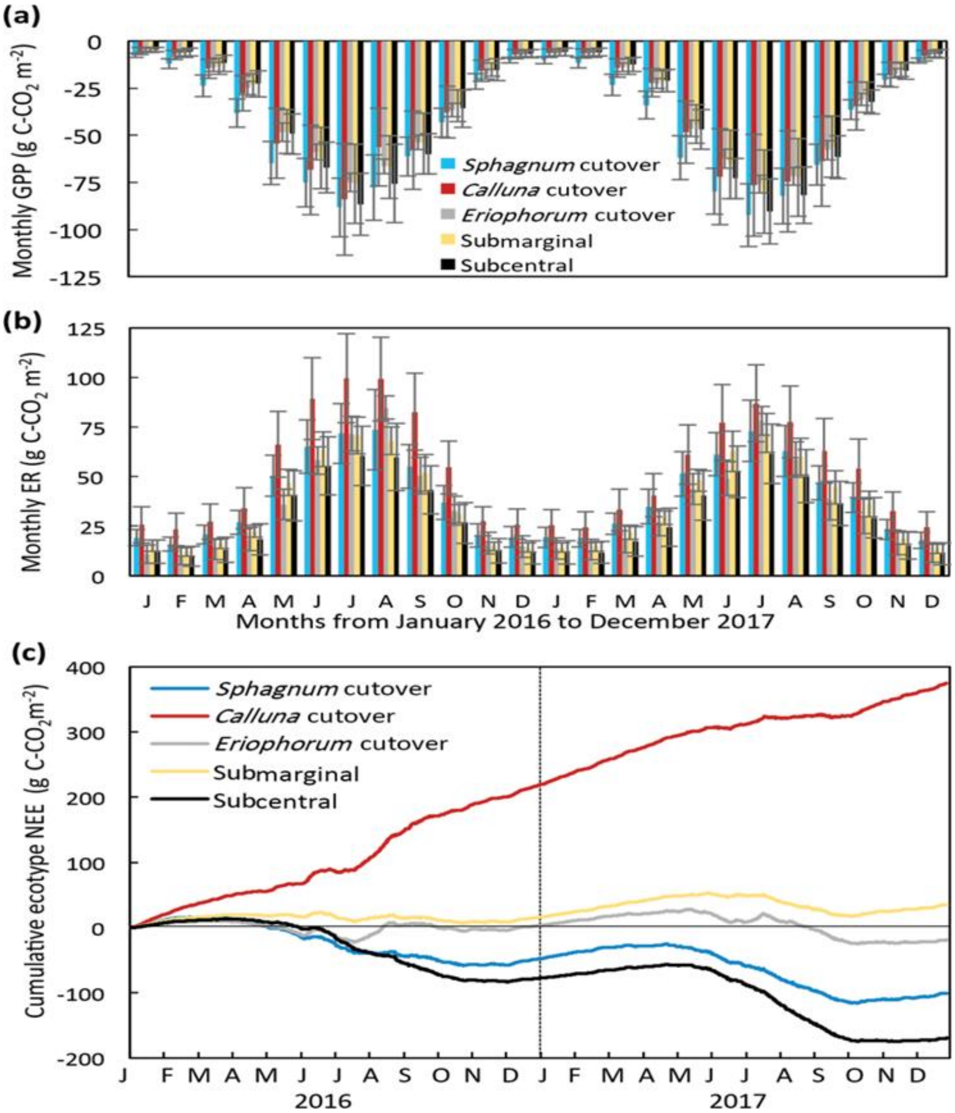


***Figure 3**: (a) Monthly GPP, (b) Monthly ER and (c) cumulative NEE for Abbeyleix ecotopes and cutover bog sites between January 2016 and December 2017. Note: values are the average of all collars in the ecotope (Swenson et al., 2019).*

REMOTE SENSING

The use remote sensing (RS) techniques to monitor changes in their ecohydrological health of wetlands was also carried out as part of the EPA funded EcoMetrics project (Gill *et al.*, 2022). The RS study used existing habitat and vegetation mapping and began with a pixel-based approach to map vegetation communities across raised bogs. The study was further extended to segment-based learning, which considers textural information in addition to spectral information, and a mapping vegetation communities (MVC) algorithm was developed (Bhatnagar et al., 2020a). In total, 29 classes were mapped temporally inside 13 wetlands using the MVC algorithm, with an average accuracy of 84%. To gain higher spatial resolution than that provided by the 10 m Sentinel-2 satellite data, an unmanned aerial vehicle (i.e., a drone) was employed (Bhatnagar *et al.*, 2020b). The ability of RS-based monitoring of wetlands was extended by a nested methodology that incorporates georeferenced land cover maps, scaled at the drone resolution level and upsampled to Sentinel-2 imagery level through interpolation - the so-called "nested drone satellite technique (Bhatnagar *et al.*, 2021) as, detailed in Figure 4.

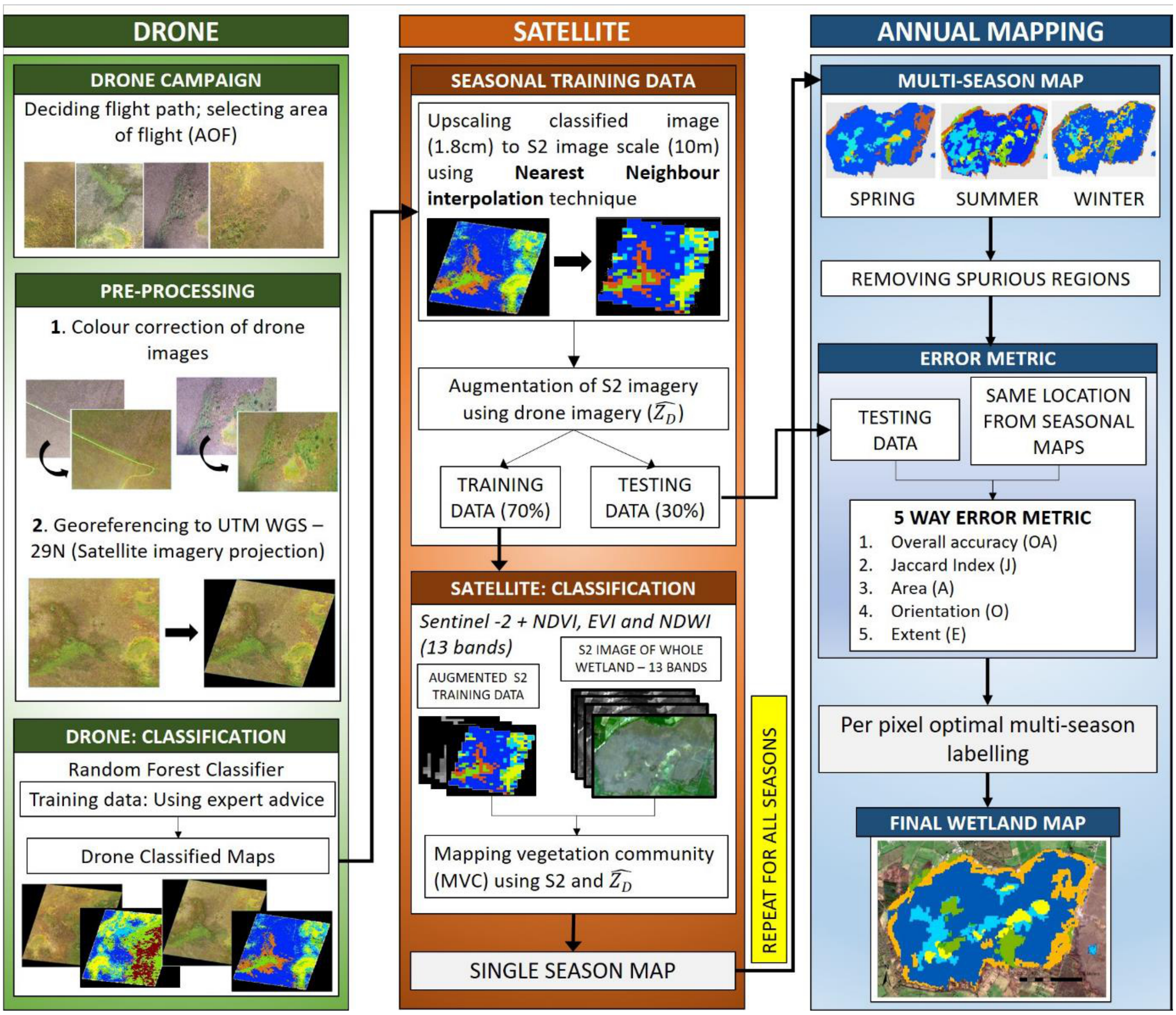


*Figure 4. Methodology flowchart for the nested drone–satellite approach to wetland mapping (Bhatnagar et al., 2021).*

## ONGOING RESEARCH – BOG RESTORATION

Ongoing research is now being carried out by the TCD Environmental Egineering group on raised bog restoration via two complementary projects: the EPA funded project, WetPeat (led by University of Galway) and an SFI (iCRAG) / Bord na Mona funded project Five bogs at different stages of restoration are being monitored as follows: Ballycon, All Saints, Catslegar, Clooneeny and Ballaghurt. These bogs have a variety of different restoration taking place from the construction of bunds, drain blocking, removal of pumps and *Sphagnum* plug inoculation.

### FIELDWORK

Each of the five bogs has had delineated sub-catchments identified which are monitored for flow at the outlet and a network of piezometers to measure water table depth across the different rewetted system. Chamber measurements for carbon dioxide and methane flux are ongoing at some sites whilst other sites have eddy flux covariance towers installed. Water quality sampling for dissolved organic matter and targeted nutrients will commence at a later stage of the project.

REMOTE SENSING

This project is using the nested drone-satellite approach to evaluate the distribution and growth of vegetation at the restored sites (particularly Ballycon which was rewetted over 10 years ago) In addition, work will commence using SAR / InSAR satellite data to attempt to monitor the water table fluctuation in the rewetted areas within the bunds and blocked drains.

MODELLING

An extensive review of peatland models that could be used for restoration has been completed (Silva et al., 2024). From this the modelling approaches that are being taken are split between the short-term hydraulic / hydrological simulation of the performance of the rewetting with respect to the target ecohydrological conditions necessary for *Sphagnum* growth and longer-term peat (carbon) accumulation models. The hydrological models currently being used are the storm drainage package SWMM to model surface flow of a cascade system of linked bunds linked by weirs between bunds and the Digibog-hydro to model the catchment response of the rewetted areas. Different combinations of the eEcosSys, Digibog, MPeat/MPeat2D and Coup Model process-based models are being investigated to determine how best to simulate long term carbon assimilation on the restored bogs. Finally, PLAXIS 2D is being used to assess the long term geotechnical stability of peat dams used to create the bunds.

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# EMBANKMENTS OVER BLANKET PEAT IN CO. DONEGAL: INTERPRETATION OF PIEZOMETER DATA

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## ABSTRACT

*A recent road improvement scheme on the N56 near Glenties, Co. Donegal, involved the staged construction of a surcharged embankment over blanket peat, enabling the peat to be left in place. This paper focusses on the interpretation of the pore pressure regime in the underlying peat during and after construction. The substantial peat strains induced by the embankment rendered buoyant the portion of the embankment that settled beneath the groundwater table and required assumptions to be made about piezometer positions. Additional assumptions necessary to arrive at coefficients of consolidation and permeabilities are presented. A hypothesis is proposed to explain the elevated long-term pore pressures noted at two of the instrument cluster locations.*

**Key words:** *embankment, peat, pore water pressure, drainage*

## INTRODUCTION

The Department of Transport has assigned ≈€8b to Transport Infrastructure Ireland (TII) this decade for our national road infrastructure. Given that 17.2% of the land area of Ireland consists of peat (Farrell 2012), it is inevitable that peat will be encountered on many future road schemes. Road projects in Ireland and elsewhere have traditionally involved substantial volumes of peat excavation, releasing carbon into the atmosphere, a driver of climate change.

Surcharging is a form of ground improvement that is often used on road construction projects to improve the engineering properties of underlying mineral soils. Surcharging entails the application of temporary overload (i.e. additional embankment height over and above final road level), thereby artificially increasing the peat's yield stress. This has the effect of front-loading the primary consolidation settlement (it occurs during construction rather than after the road surface is in place) and can also reduce long-term secondary/creep settlements. Importantly, the use of surcharged embankments on peat would enable the peat to remain *in situ*, thereby retaining its carbon store. However, surcharging is not currently permitted by Transport Infrastructure Ireland (TII Series 600, 2013) in highly organic soils including peat, nor is it widely used internationally in these soils.

The N56 Letterilly to Kilraine road improvement scheme (near Glenties, Co. Donegal), completed in 2022, afforded the opportunity to explore the potential of surcharging at a blanket peat site; excavate-and-replace was excluded due to ecological constraints and therefore a surcharging solution was permitted by TII on an exceptional basis. Given the novelty of the approach, a significant embankment monitoring programme was conducted as part of the scheme. An overview of the scheme is provided by Kissane *et al.* (2024), while Fattahi Masrour *et al*. (2024) focus on embankment primary consolidation performance at one location along the mainline. The focus of this paper is on pore water pressures in the peat during and after construction: the challenges in interpreting the pore pressures from piezometers given the large strains involved, and the likely effect of settlement on peat permeability.

## N56 LETTERILLY TO KILRAINE IMPROVEMENT SCHEME

The project involved the redevelopment of a 4.5 km section of the N56 national secondary route, immediately north of Glenties, Co. Donegal. A multi-stage surcharged embankment (Figure 1a) was implemented along ≈1.5 km of the road. In order to inform the embankment staged-loading hold periods and assess embankment stability and peat settlements, six instrument clusters (ICs) were established along the road alignment; each IC incorporated a foundation settlement plate (FSP), a subsurface profile gauge (SSPG), a vibrating wire piezometer, and an inclinometer pair, one on each side of the road. An example cross-section (IC1), depicting the instruments, is shown in Figure 1b. A longitudinal section with relevant levels and IC locations is shown in Figure 2. To the west of the road alignment, a low-height unsurcharged control embankment (with three FSPs and a piezometer) was constructed to aid an assessment of the effect of surcharge magnitude on creep settlements. The peat properties at the site are provided elsewhere (Kissane *et al.* 2024, Fattahi Masrour *et al*. 2024).

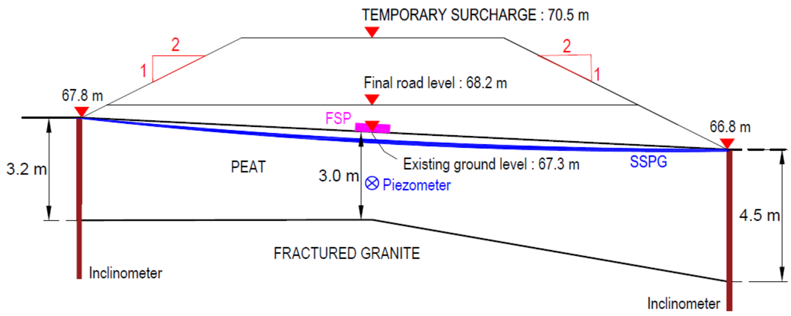


***Figure 1:*** *(a) Surcharge removal at N56 Letterilly to Kilraine (Glenties) site, (b) Cross section at IC1 depicting embankment levels, peat thickness and instrumentation*

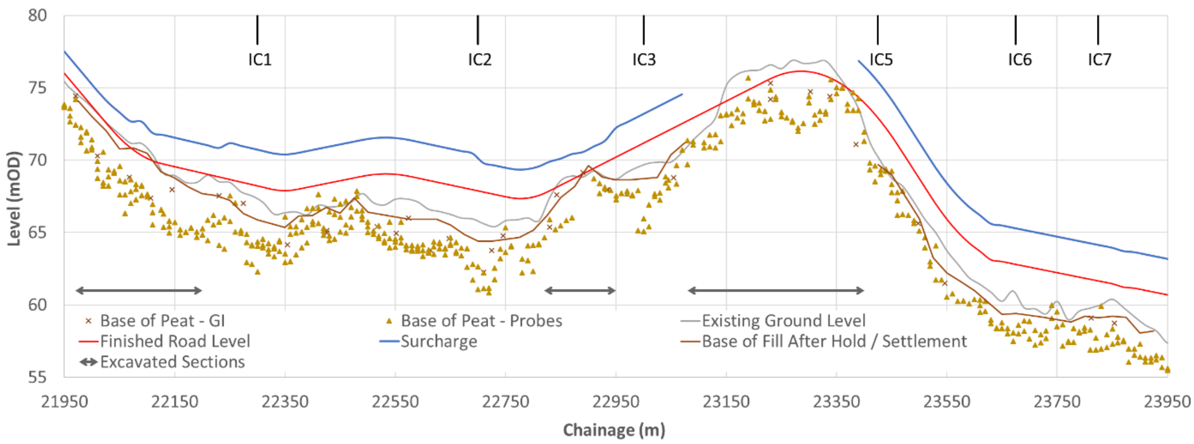


***Figure 2:*** *Longitudinal section showing relevant levels and IC locations*

## EXAMPLE SETTLEMENT AND PORE PRESSURE DATASET (IC1)

An example dataset (IC1) showing the evolution of total stress with time corresponding to staged embankment construction (eight stages in this case) is shown in Figure 3. The total stress is that corresponding to the level of the piezometer within the peat, initially 1.7 m below original ground level (for consistency with pore pressure data also plotted in Figure 3).

When a total stress increment (such as embankment loading) is applied to a saturated soil, the pore pressure in the underlying soil assumes all of this stress initially. This generates a hydraulic gradient between the underlying soil and that located more remotely, leading to pore pressure dissipation (and effective stress increase) over time. The rate of pore pressure dissipation reflects both the rate of total stress application and the permeability of the soil. The increases in excess pore pressures (i.e. over and above initial free-field values) within the peat and subsequent partial dissipation, in response to the eight loading stages, are apparent in Figure 3. Both corrected and uncorrected versions of total stress and pore pressures are included, which will be explained in the next section.

Primary settlement (Figure 3, IC1) occurs as a result of pore pressure dissipation; trends shown are based on the FSP and the SSPG reading closest to the embankment centre. Based on a peat thickness of 3 m, the settlements at the point of surcharge release correspond to vertical strains of ≈46% (FSP) and ≈41% (SSPG). These values may also include small amounts of creep settlement, which arises due to re-arrangement of particles upon reduction in water content (i.e. not related to changes in effective stress). Creep settlement continues long term and can be quantified more readily once primary consolidation is complete.

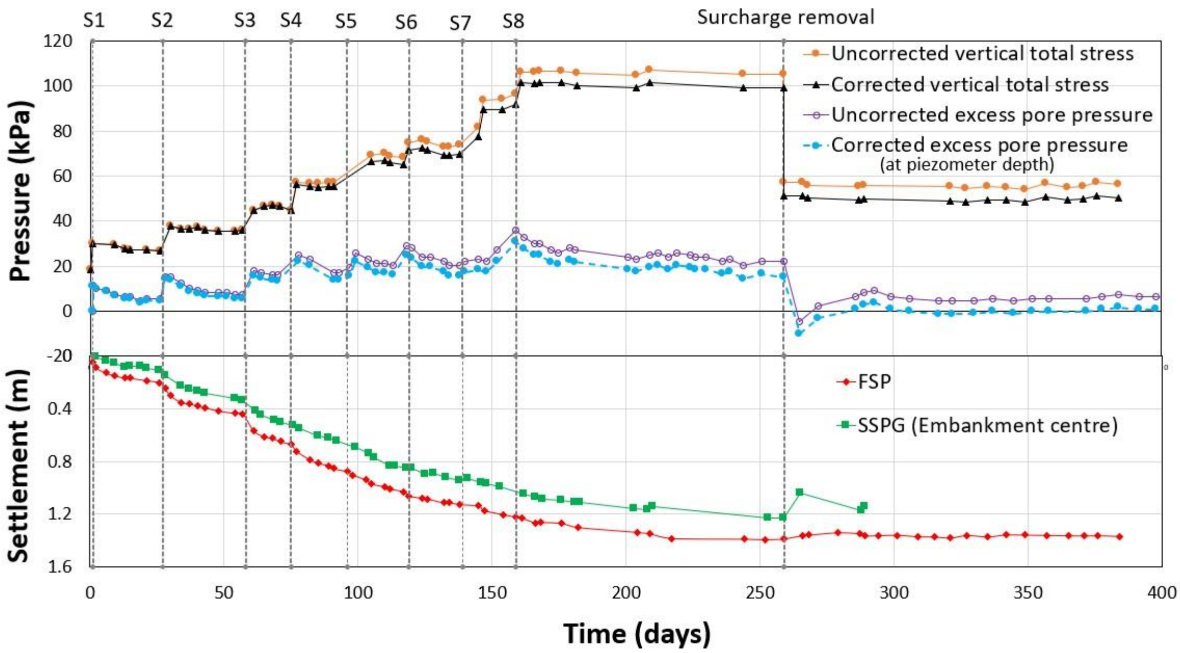


***Figure 3:*** *Evolution of vertical total stress, excess pore pressure and settlement with time.*

## PORE PRESSURE INTERPRETATION

The interpretation of the pore water pressure regime underneath the embankment was not straight-forward; key considerations are summarised in the following sections. Many of these relate to the large strain nature of the problem and have been highlighted by Arulrajah *et al.* (2004) in context of a trial embankment on soft marine clay in Singapore.

### BUOYANCY

Once the settlement of the embankment exceeded the depth to the groundwater table, the portion of the embankment below the water table become buoyant, prompting a correction to the total stresses (see Figure 3, IC1). Submergence of the fill also caused a small reduction in external load during the consolidation process as settlement progresses.

## PIEZOMETER SETTLEMENT

Piezometers settle in tandem with the soil in which they are installed and therefore the original datum (near the midpoint of the peat stratum) will change over time. This is particularly pronounced in large strain scenarios such as in embankments constructed on peat.

For example, the instrument at IC1 was initially 0.25 m below mid depth. Assuming (i) that the peat thickness is uniform, (ii) peat properties are consistent with depth (water contents and shear wave velocities indicate that this is the case; see Fattahi Masrour *et al.*, 2024) and (iii) little decay of the embankment total stress with depth within the peat, it is assumed that the piezometric datum reduced by (3 m - 1.75 m)/3 m or 42% of the surface settlement at any time. For IC1, the final excess pore pressure correction applied at the end of stage 8 is ≈6 kPa (i.e. an assumed 0.6 m settlement of the instrument), see Figure 3.

## DEGREE OF DISSIPATION

The measurement of pore water pressure at a specific depth within a soil layer undergoing consolidation enables the progress of consolidation (and primary settlement) at that depth to be assessed. It does not reflect the average degree of consolidation in the layer, which is what dictates surface (and therefore embankment) settlement. A double drainage isochrone, based on Terzaghi's theory of consolidation, was used to infer the average degree of consolidation in the peat layer from the single piezometer reading. Double drainage was assumed based on the existence of fractured granite beneath the peat (Russian sampler log), and a thin sand layer 100 mm thick detected by the CPT ball.

Fattahi Masrour *et al.* (2024) concluded that the use of settlement measurements, interpreted in conjunction with the Asaoka (1978) method, is a better means of estimating the degree of dissipation, given the number of assumptions involved in interpreting pore pressure data.

## COEFFICIENTS OF CONSOLIDATION

The coefficient of consolidation ($c_v$) is a parameter which dictates the rate of pore pressure dissipation and corresponding evolution of primary settlement. Values of $c_v$ were computed from the degree of dissipation values in the peat along the mainline and under the control embankment. It was not possible to estimate $c_v$ for most of individual stages along the mainline due to insufficient pore pressure dissipation, but a global estimate was possible, assuming that the maximum load was applied in a single increment at the midpoint of the staged construction process (see Fattahi Masrour *et al.* 2024 for full details). The values of $c_v$ ranged between 0.45-2.1 m$^2$/year along the mainline (maximum vertical effective stresses in the range 40-97 kPa) and 115 m$^2$/year for stage 1 of the control embankment (maximum vertical effective stress of 27 kPa), showing the dramatic reduction in $c_v$ with vertical effective stress known to occur in peat (e.g. Carlsten 1988). These values are lower than those derived using the Asaoka (1978) method, which are 2.0-8.6 m$^2$/year for the mainline and 121 m$^2$/year for stage 1 of the control embankment. Arulrajah *et al.* (2004) also concluded that the Asaoka (1978) method produced higher values of $c_v$ than those deduced from pore pressures.

## PERMEABILITY REDUCTION IN PEAT – A HYPOTHESIS

Corrected excess pore pressures for IC1, IC2, IC3, IC5, IC7 and the control embankment are shown in Figure 4 (no piezometer at IC6). For IC1, IC5, IC7 and the control embankment, the piezometer position correction results in zero excess pore pressures after surcharge removal, as expected. However, elevated excess pore pressures of 5-10 kPa were noted at IC2 and IC3 after surcharge removal. A mechanism is postulated below to explain how this might have occurred (see Figure 5, illustrated for IC1), requiring all of the following:

(i) Significant compression arose underneath the embankment at most of the IC positions. Based on the SSPG measurements at IC1 for example, peat strain was at least 30% within the central 12 m of the embankment width (Fattahi Masrour *et al,* 2024).

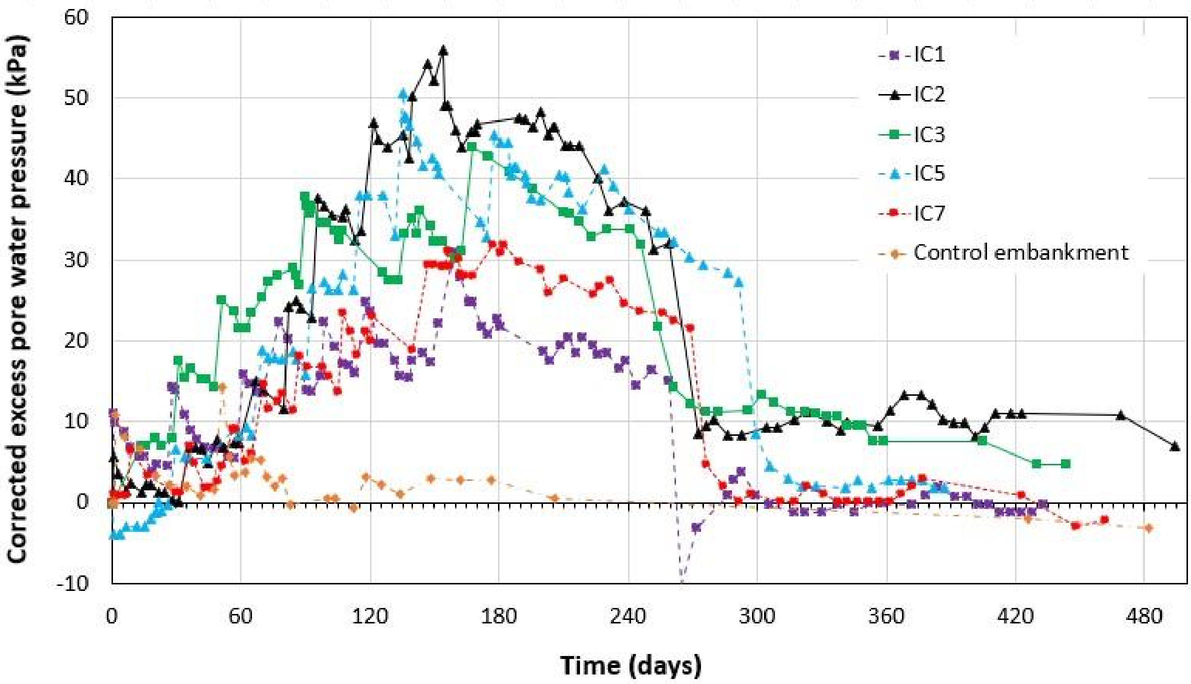


***Figure 4:*** *Excess pore pressures at IC (mainline) and control embankment locations.*

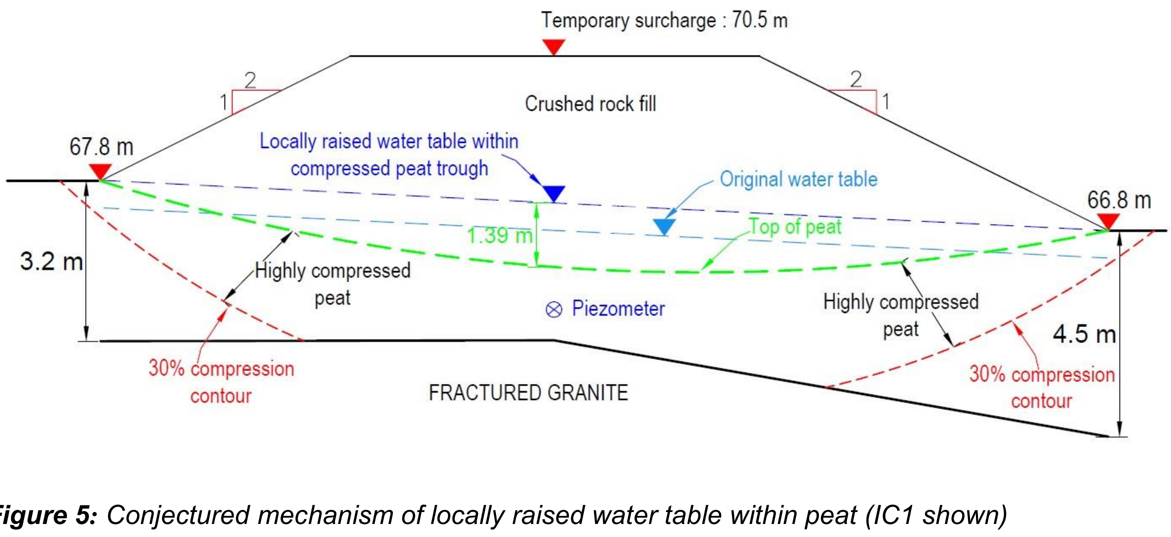


***Figure 5:*** *Conjectured mechanism of locally raised water table within peat (IC1 shown)*

(ii) Hanrahan (1954) reported a reduction in permeability of ≈60 for Irish peat due to a void ratio reduction of 35%. Hobbs (1986), presenting an envelope of data from ≈100 tests from various countries, suggested a reduction in permeability of at least 10 for a void ratio reduction from 15 to 10. The initial void ratio at the N59 site averaged 15 (*in situ* moisture contents averaged ≈1000%) and a similar reduction in void ratio or strain level arose to those quoted above. Using the Asoaka-derived $c_v$ values, the permeability for stage 1 of the control embankment was calculated as $2.3\times10^{-7}$ m/s (27 kPa: low stress), falling within the limits quoted by Mesri and Ajlouni (2007) for a void ratio of 15 at *in situ* stress levels. The permeability range for the mainline was one to two orders of magnitude lower: $2.1\times10^{-9}$-$1.1\times10^{-8}$ m/s (40-97 kPa: higher stress), in keeping with the large reductions described above. These reductions, in addition to the deformed peat-fill interface, will create a shallow 'trough' of free-draining fill surrounded by relatively impermeable peat extending to the surface (and possibly above due to heave beyond the embankment toes).

(iii) A combination of rainfall infiltration and gravity groundwater flow can drain into this newly formed trough. Depending on the vertical alignment of the road and the depressed peat surface following surcharge application and removal, water can become trapped in this zone. Local low spots in the base of the fill at IC2 and IC3 (Figure 2) meet the requirements of the hypothesis. Water can outfall from this trough at either the existing ground surface near the embankment toe or at transverse cross ditches constructed at drainage culverts or sections where excavation and replacement was performed.

## CONCLUSIONS

The interpretation of the pore pressure regime in a soil layer from a piezometer, and in turn the degree of dissipation and coefficients of consolidation, is complicated in large-strain scenarios, such as the construction of high embankments over peat. Issues identified in this paper include: (i) buoyancy of the portion of fill which has settled beneath the water table, (ii) uncertainty in relation to the piezometer position (and therefore the pore water pressure datum) within the settling mass, (iii) drainage boundary conditions, and (iv) extrapolation of the degree of dissipation at one level within a layer to an average degree of dissipation over an entire layer.

It is postulated that the large strains within the peat may give rise to a significant localised reduction in permeability near the top of the peat. This relatively low permeability settlement trough, filled with highly permeable rock fill, is conjectured to contribute to the elevated excess pore pressures once the surcharge was removed at two of the IC positions.

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# NATURAL SOURCE ZONE DEPLETION: LEARNINGS FROM FIELD SCALE ASSESSMENT ON AN OPERATIONAL FACILITY

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## ABSTRACT

*Natural source zone depletion (NSZD) has emerged as a highly sustainable remedial option for LNAPL impacted sites. WSP undertook one of the first large scale field studies in the UK, assessing NSZD rates from a LNAPL plume in an operational industrial setting. The NSZD assessment was completed on a well delineated LNAPL plume with an extensive monitoring dataset and established regulatory awareness. The assessment focussed on vapour phase flux, though dissolved phase mass flux rates were also quantified. Surface measurements via dynamic closed chamber (DCC) and passive traps as well as the gradient method were utilised to derive mass flux estimates. Vapour phase mass flux was dominant, consistent with published research and pre-study expectations based on the source hydrocarbon properties. The DCC method of measuring surface $CO_2$ flux proved to be the most effective at deriving a robust and repeatable mass depletion estimates, in the operational setting. Mass depletion rates calculated during the study were consistent with the published ranges, on the order of 1000's l/yr. The outcome of the trial verified the action of NSZD processes at the study site and the regulator agreed that NSZD could potentially form a key component of the remediation of the LNAPL plume. The study demonstrated that NSZD can be quantified in an operational setting and that it is possible to consistently and repeatedly derive mass depletion rates which benchmark favourably against other, more active but less sustainable remediation approaches.*

**Key words:** *Natural source zone depletion, LNAPL, sustainable remediation.*

## INTRODUCTION

Natural Source Zone Depletion (NSZD) represents a highly sustainable remedial option for Light Non-Aqueous Phase Liquid (LNAPL) plumes which has the potential to reduce reliance on traditional, more carbon-intensive, remediation techniques. The majority of NSZD studies published to date have been based in the USA and Australia, in regions where the climate and geology (both key factors influencing NSZD rates) can be very different to those in northern Europe.

The project described in this paper was one of the first in the UK to apply NSZD quantification methods at a large field scale. The trial to quantify the rate at which NSZD occurred was designed to allow the assessment of the suitability of an attenuation based remedial approach for the LNAPL plume. The application of the novel techniques required considerable regulatory engagement before the trial was implemented.

The successful application of NSZD quantification in an operational UK setting, combined with other recently published sustainable remediation case studies (Concawe, 2023) represents a significant step towards establishing a suite of more sustainable remedial options for LNAPL plumes. Consideration of NSZD and its influence on LNAPL management is increasingly now becoming part of industry best practice, through materials published by both European (Concawe, 2022) and US (ITRC, 2018) industry bodies.

This paper summarises the context and conceptual site model that supported the consideration of NSZD as a potential remedial solution for this project as well as outlining the sustainability assessment completed. Key aspects of the approach to dialogue with key stakeholders including the client and local regulator are also presented.

## BACKGROUND AND CONTEXT

The site which is the subject of this NSZD case study is an operational UK Oil and Gas Sector facility. The LNAPL present within the defined source zone:

- Lies within an unconfined aquifer beneath an area of predominantly unsealed ground;
- Primarily comprises a highly volatile mixed hydrocarbon product; and
- Is located within the seasonal groundwater smear zone, primarily at depths between 3.5 and 5.0 m below ground level (m bgl).

Following multiple phases of intrusive investigation and several years of regular groundwater monitoring, the LNAPL body was identified as suitable for NSZD assessment. The key supporting pillars developed during the monitoring phase which allowed both the site operator and regulator to buy into the concept of NSZD as a potential remedial option were:

1. Data obtained during the extensive monitoring phase had provided high confidence in both LNAPL and dissolved phase plume stability.
2. Detailed quantitative Human Health and Controlled Waters risk assessments completed in advance of the NSZD assessment had established an absence of unacceptable risk to identified receptors (offsite residents, downgradient aquifers and surface water bodies).
3. During the delineation and monitoring phase, mass recovery via skimming had been undertaken from the LNAPL source zone. LNAPL recovery rates had markedly reduced during this period of active recovery.

Works completed throughout the NSZD assessment were designed to be compatible with requirements at an active facility and minimise impacts on routine site operations. Constraints such as the use of equipment in potentially explosive atmospheres (ATEX zones) had to be considered throughout the design and implementation of the NSZD monitoring programme.

## CONCEPTUAL SITE MODEL

At the outset of the trial phase NSZD represented a novel remedial option with very little track record of application in the UK and an absence of established industry guidance. As such effective engagement with key project stakeholders required clear and coherent communication of NSZD principles.

A robust and comprehensive LNAPL conceptual site model (CSM), developed through the site investigation, monitoring and testing phases, was required. The principal elements of the LNAPL CSM are illustrated in Figure 1.


***Figure 1:** LNAPL CSM Components (Concawe 2023)*

NATURE AND EXTENT

The source zone covered a surface area of approximately 1 hectare and had formed from a discrete release event >10 years before commencement of the NSZD study. The majority of LNAPL mass within this source zone was present within the groundwater smear zone. The geology underlying the source zone consisted of unconsolidated granular material, predominantly comprising sands and gravels. Local heterogeneity was present within these shallow superficial deposits (including cohesive lenses). The ground surface in the source zone and downgradient areas was predominantly unsealed. Surface cover and geology in surrounding areas at the site was consistent with the source zone allowing background monitoring locations to be identified. Representative background locations are necessary to evaluate vapour phase mass flux attributable to LNAPL depletion when using certain surface based NSZD monitoring techniques (API, 2017).

The long-term monitoring dataset indicated that LNAPL was stable at the plume scale. A consistent footprint of measurable LNAPL was recorded over several years prior to the commencement of the NSZD trial. The groundwater smear zone was typically encountered from 3.5 m below ground level (bgl). Seasonal variation in the depth to the saturated zone of 1.0 to 1.5 m was recorded annually. The LNAPL mass was present under unconfined conditions, as demonstrated by the variability of both air-NAPL and NAPL-water interfaces in individual monitoring wells (Figure 2). The simultaneous variation of both the Air-NAPL and NAPL-Water interfaces in monitoring wells across the source zone, illustrated in the example Diagnostic Gauge Plot are indicative of unconfined conditions (Hawthorne, 2011).

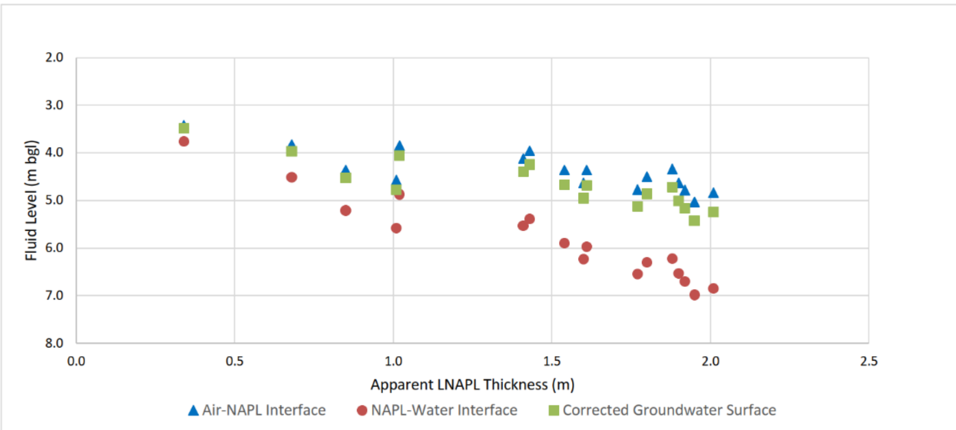


***Figure 2:** Single Well Diagnostic Gauge Plot, LNAPL Plume Centre (modified from Concawe 2023)*

COMPOSITION

Data from multiple phases of product sampling prior to and during the NSZD trial identified a consistent source LNAPL composition, characterised by:

- Mixed source, predominantly C5-12 aliphatic and aromatic carbon chain fractions with some longer chain elements also present;
- Significant (but decreasing) benzene, toluene, ethyl-benzene and xylene (BTEX) component; and
- No oxygenates were present.

Field observations recorded during the investigation and monitoring phases consistently demonstrated the volatile nature of the LNAPL source, through visual and olfactory evidence and field screening of soil samples during phases of intrusive investigation.

The volatility of the source LNAPL highlighted potential for significant vapour phase mass degradation, via physical partitioning subsequent biodegradation in the unsaturated zone.

Time series analysis of product sample analytical data highlighted LNAPL composition changes indicative of active degradation processes, most notably the reductions in C17:Pristane ratios (Hurst & Schmidt, 2005).

STABILITY

Routine gauging and groundwater sampling data described the presence of a stable LNAPL and dissolved phase plume.

The stability of the LNAPL plume (Figure 3) remained consistent throughout the NSZD trial with apparent LNAPL thicknesses (>1m) restricted to five monitoring wells in the plume centre. Apparent LNAPL thickness in all monitoring wells remained within the historical ranges throughout the trial. Seasonal variation in apparent LNAPL thickness was observed consistent with data collected over multiple years during the pre-trial monitoring phase.

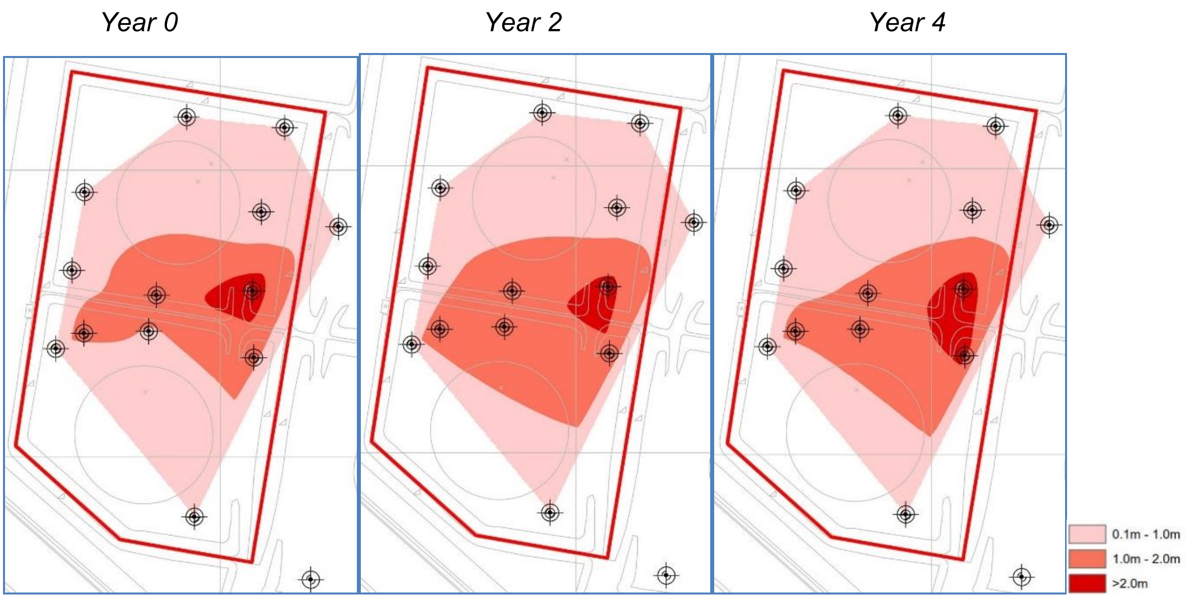


***Figure 3:*** *Median LNAPL Thickness in Monitoring Wells During NSZD Assessment (Concawe 2023)*

RECOVERABILITY

Prior to the NSZD assessment, following early phases of intrusive investigation, LNAPL recovery was first implemented from a single well, then expanded to encompass multiple wells. The expanded system comprised multiple LNAPL skimming pumps. Average recovery rates from the skimming system (initially 100's litres/day) exhibited a declining trend over time with rates reducing to approximately 10 l/d.

LNAPL transmissivity testing was undertaken at multiple wells in the source zone prior to the NSZD trial. Derived LNAPL transmissivity values (0.01 – 0.07 $m^2$/day) were consistent with the lower threshold for effective recovery based on published literature values (ITRC, 2009).

Indicators of active LNAPL degradation were identified throughout the investigation and monitoring phases. The majority of the degradation evidence collected prior to the NSZD study was focussed on saturated zone mass depletion processes.

Analytical data from LNAPL sample testing was indicative of high vapour phase degradation potential (consistent with field observations) with a relatively high abundance of volatile and higher solubility carbon chain lengths.

In downgradient areas evidence indicative of active natural degradation of dissolved phase hydrocarbons was consistently recorded, directly through the reduction in concentrations of dissolved phase hydrocarbons over time and indirectly through the spatial distribution of electron acceptors.

The NSZD assessment described below facilitated the quantification of the rates of LNAPL mass degradation, focussed on vapour phase flux which was expected to dominate mass degradation.

## NSZD ASSESSMENT TRIAL

All three techniques recommended in the API (2017) guidance were trialled during the study, to appraise feasibility of application in a UK operational setting.

- 15 passive traps were deployed for two monitoring rounds, each lasting at least two weeks.
- >2,000 $CO_2$ flux readings were collected using a Dynamic Closed Chamber (DCC), from 47 locations (including background locations), over a 12-month period.
- Soil vapour samples were collected from three vapour well clusters. Clusters comprised adjacent soil vapour wells with discrete (15 cm) response zones offset at 0.5 m intervals within the unsaturated zone (Figure 4).

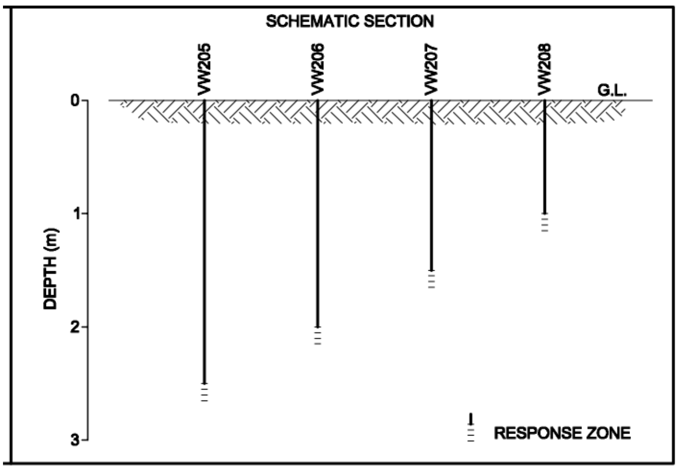


***Figure 4:*** *Vapour Well Cluster – Source Zone (WSP)*

NSZD - DESIGN & COMMUNICATION

Following a period of internal stakeholder engagement, utilising the LNAPL CSM, a proposal to cease LNAPL recovery and formally assess mass degradation attributable solely to NSZD was presented to the local regulator.

WSP and the client were acutely aware that the assessment and potential application of a novel technique such as NSZD required detailed communication and planning, with particular emphasis on residual uncertainties within the LNAPL CSM. To effectively manage plume status and any potential adverse changes in risk profile during the NSZD trial, contingency plans were developed and agreed with the regulator. These included increasing the frequency of groundwater monitoring downgradient of the source zone and development of a clear set of response actions together with associated trigger criteria.

## NSZD ASSESSMENT OUTCOMES

Consistent with published research, vapour phase flux was demonstrated to be the dominant mass transfer mechanism (orders of magnitude in excess of saturated zone mass flux).

The DCC (Li-Cor 8100A, shown in Figure 5) provided the most effective monitoring method in the operational setting. The inherent flexibility provided through the combination of short measurement duration and the ability to obtain data in real time in the field, was identified as a significant advantage in this project. It is however recognised that in other project settings the other available NSZD monitoring techniques may be preferred.

Being the one of first UK field scale application of the technique, limited precedent data existed against which to establish an expected baseline. The ability to review and rapidly react to data as it was collected in the field was a significant advantage of the DCC technique. A significant commissioning period was required early in the study to identify suitable background locations (a challenging constraint in an operational environment) and quantify diurnal variations in observed surface flux (typically 50-60%) at the project site.

***Figure 5:*** *CO2 Flux Monitoring with Dynamic Closed Chamber (Concawe, 2023)*

The mass flux derived through surface (DCC) monitoring varied seasonally over an annual cycle between approximately 940 – 6,550 l/ha/yr. These rates were consistent with the lower end of the ranges recorded from published research (Garg et al 2017). Mass flux estimates of a similar magnitude were obtained using the gradient method.

The significant seasonal flux variations recorded were expected given the wetter climate in the UK compared with continental US examples which typify where these techniques have been applied previously. Soil moisture and temperature logging on site, as well as soil vapour profiling all formed crucial supporting data for the interpretation of surface $CO_2$ flux.

## SUSTAINABILITY ASSESSMENT

Consideration of the three concepts set out in Figure 6 (which underpin the basis for deciding an appropriate course of remediation for any site), identified NSZD as a potential remedial solution in this case.

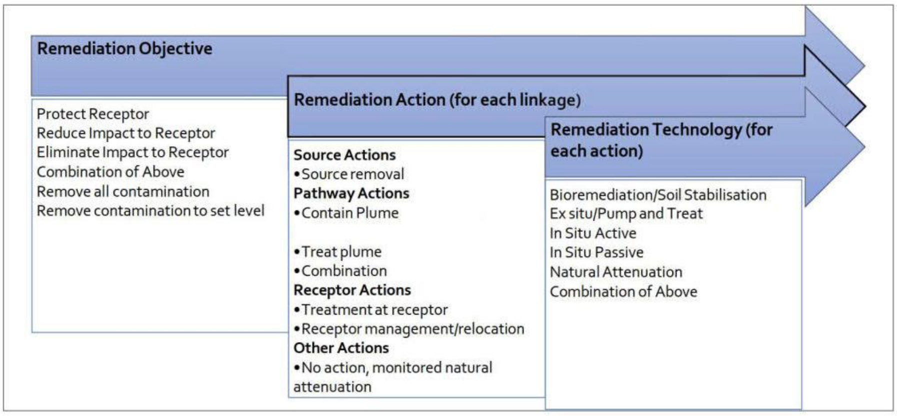


***Figure 6:*** *Relationship Between Remediation Objectives, Actions and Technologies (Concawe, 2023)*

**Remediation Objectives:** The remediation objectives determine the overall technical intent of the project.

**Remediation Action:** The conceptual approach to achieving the identified remediation objective, defined specifically in terms of contaminant linkages which each action addresses.

**Remediation Technology:** The specific tools that will be employed to fulfil each remediation action.

To formalise the sustainability benefits an 'attenuation based' approach in this case, implementing NSZD was assessed against an alternative remedial option through qualitative comparison against the 15 headline United Kingdom Sustainable Remediation Forum (SURF-UK) indicators (CL:AIRE, 2020).

***Table 1:*** *Qualitative Assessment Summary*

| Indicator Category | Attenuation Based | Dual Phase Extraction |
|---|---|---|
| Environmental | Better | Worse |
| Social | Equal | Equal |
| Economic | Better | Worse |
| Overall | Better | Worse |

As expected, preliminary screening indicated that an 'attenuation based' remedial strategy, founded on NSZD provides a more sustainable option than dual phase extraction. Sustainability benefits of an 'attenuation based' approach were most significant for Environmental and Economic headline indicators.

## PROJECT HIGHLIGHTS

The NSZD study was successful in proving the significance of natural mass depletion processes for the LNAPL plume and demonstrating that the monitoring of NAPL mass depletion rates could be achieved at an operational UK facility. Following the initial trial phase an annual mass depletion rate was quantified which benchmarked well with previously published mass depletion rates from global studies. The findings and conclusions of the study were accepted by the regulator and a phase of further data collection has been approved.

The study was subsequently short-listed at the 2022 UK Brownfield Awards, in the 'Best Research, Innovation or Advancement of Science in the Brownfield Sector'.

PRINCIPAL FINDINGS

Total $CO_2$ flux measured in the source zone was consistently higher than recorded at background locations, in line with the key assumption underpinning the DCC method.

The trial recorded effective LNAPL mass depletion rates within the lower range of published research values, consistent with the wetter and cooler climate of the UK. An annual average of approximately 3,300 l/ha/yr was calculated. The study was completed with full UK regulator engagement and acceptance of the study findings paved the way for development of a long term NSZD remedial strategy.

As predicted, in line with published research, saturated zone mass flux was several orders of magnitude lower than vapour phase mass flux.

With successful outcomes now reported back to both site operator and regulator, further NSZD monitoring data is being collected augmenting the initial dataset with a view to developing, and gaining endorsement for, a full NSZD strategy for the remediation of the LNAPL mass.

## LESSONS LEARNED

The following key learnings were obtained through the trial period regarding the design and implementation of NSZD assessment. It is recommended that these learnings are considered when NSZD is under consideration as a potential remedial option:

- Early engagement with the client is vital – NSZD is likely to represent a long-term commitment if pursued as a remedial technique.
- Be clear about uncertainties – time taken early in the process to increase confidence in the conceptual site model will provide value throughout the project lifecycle.
- Engagement with the regulator should be proactively sought and is recommended as a key component in successfully implementing NSZD as a remedial option.
- On operational sites, ensure monitoring programmes are designed to manage all site constraints and critical safety controls.
- Contingency plans should be developed to specify actions and agreed responses in the event that changes to the CSM are recorded that could potentially limit the applicability of an 'attenuation based' remedial approach.
- A flexible field monitoring programme may be required to allow adaptation of the assessment as data are reviewed.

Following endorsement for the NSZD trial phase by internal stakeholders (client), a detailed consultation with external stakeholders (regulator) was undertaken focussing on achieving a consensus in relation to the following aspects:

1. The supportive LNAPL CSM which underpinned the proposed NSZD assessment, including the outcome of detailed assessment of risks;
2. The technical theory underpinning NSZD and the proposed methodologies to be employed alongside performance indicators (what success looks like);
3. The relevant performance metrics and contingency measures that would be in place during the trial phase; and

4. A clear timetable including agreed reporting dates.

This consultation phase took several months but facilitated the development of a trusted relationship between stakeholders which is vital to support the application of an innovative technique.

## CONCLUSIONS

The NSZD assessment presented in this case study, believed (based on discussions with the regulator) to be the first UK field scale trial of these monitoring techniques, resulted in enhanced understanding of:

- Deployment of NSZD monitoring techniques in an operational site setting; and
- Communication of NSZD data collection methods and results to external stakeholders.

The trial phase indicated that a flexible surface flux-based method (DCC) can be successfully employed in a UK setting and that supporting vertical profiling of soil gas provides increased confidence in the interpretation of surface mass flux results.

The sustainability benefits that an NSZD based remedial option can provide should be considered early in the options appraisal process with the assessment of these benefits refined during any trial phase.

A mass flux range of approximately 950 – 6,500 l/ha/yr was recorded. At the plume scale depletion rates of this order can result in significant source mass removal. NSZD can represent a highly sustainable remedial option in supportive conditions where a volatile source LNAPL is present, even in the UK and facilitate transition from active remediation (Statham et al 2023).

It is noted that observed surface flux was highly seasonal and care should be taken to fully characterise and understand the mechanisms for this in any assessment.

Before NSZD can be considered as a remedial option a significant period of investigation and monitoring is required to develop a sufficiently robust LNAPL conceptual site model.

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# PEATLAND RESTORATION IN IRELAND: A POWERFUL NATURE BASED SOLUTION

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## ABSTRACT

*Peatlands cover a significant proportion of the Irish Landscape. Despite legal protection of many raised bogs and blanket bogs under legislation transposing the EU Habitats Directive, degradation of these habitats has continued. This not only results in the loss of a unique and globally rare habitats, but a loss of potential ecosystem services benefits these habitats can provide. Potential ecosystem services include biodiversity, supporting a range of specialist flora and fauna, providing a supporting function to downstream aquatic ecosystems and regulating flows in our rivers. Preserving our existing healthy peatlands and restoration of those that have been subject to degradation therefore offers a powerful nature-based solution to a wide range of issues. However, despite its widespread application, the impacts of ditch blocking on peatland hydrology remain poorly quantified, particularly in Irish blanket bogs. A four-year study, monitoring water table level (WTL) responses to ditch blocking using peat dams, on a lowland blanket bog in Ireland, aimed to quantify the effects of restoration measures in a range of hydrological settings. Analysis of WTLs before and after restoration revealed summer (April-September) WTLs became shallower across a wide range of topographic conditions. Median summer water levels proved shallower (≥1 cm) at 89% of monitored locations with an average median summer WTL increase of 4 cm (± 6 cm). Drain orientation, surface slope and contributing catchment area were found to be key influences on WTL response, and therefore on the magnitude of impacts from drainage. Findings demonstrate the need for adequate baseline and post-restoration monitoring data to make robust conclusions on the hydrological impact of ditch blocking.*

**Key words:** Peatlands, bogs, hydrology, groundwater, restoration, water table levels.

## INTRODUCTION

Peat soils cover approximately 20% of the Irish landscape (Hammond, 1981). Their occurrence is strongly associated with climatic and geological conditions, with most raised bogs occurring throughout the Irish midlands along with pockets along the Lough Neagh/Bann valley and along the mouth of the River Shannon in North County Kerry and County Clare (Figure 1). Blanket bogs, which are more widespread than raised bogs, occur in areas with higher rates of rainfall, particularly along the western coast of Ireland and in upland areas throughout the island. Historically, bog formation often was considered to occur largely in isolation from underlying deposits (Ingram, 1983; Bragg, 2002). However, this is an over-simplification, with many bogs displaying strong groundwater dependency (Regan et al., 2019). Indeed, geological conditions were fundamental in controlling where peat formation occurred, influencing not only the vegetation that initially developed but also the topographic and hydrogeological conditions that permitted peat to form. This has important implications when considering the potential ecosystem services that peatlands can provide when maintained in a healthy condition. Potential benefits from peatland restoration include biodiversity benefits in maintaining unique and globally scarce habitats, supporting a range of specialist flora and fauna, providing a supporting function to downstream aquatic ecosystems (Flynn et al., 2021; Kuemmerlen et al., 2022), and regulating flows in our rivers (Acreman and Holden, 2013; Allott et al., 2019; Bain et al., 2011; Wilson et al., 2011). Preserving our existing healthy peatlands and restoration of those that have been subject to anthropogenic degradation therefore offers a powerful nature-based solution to a wide range of issues.

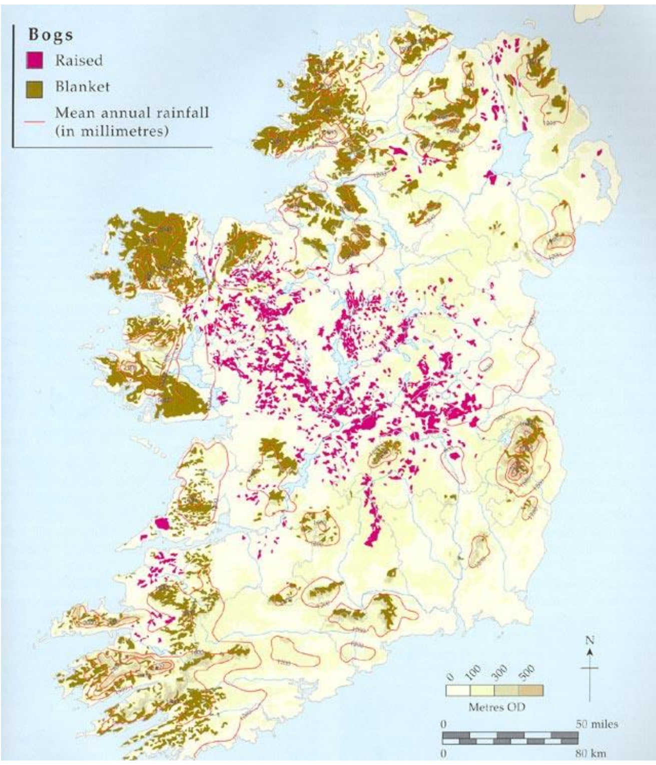



***Figure 1:*** *Map illustrating occurrence of raised bogs and blanket bogs across Ireland (Source: Aalen et al., 1997)*

## CURRENT CONDITION OF PEATLANDS IN IRELAND

### CONSERVATION STATUS

In recognition of their ecological importance raised bogs and blanket bogs are listed for protection under Annex I of the European Union Habitats Directive (HD) (European Union Directive 92/43/EEC). More specifically, active raised bogs and active blanket bogs (i.e., those which are still supporting significant areas of peat-forming vegetation) are classified as priority Annex I habitats under the HD. These habitats are subject to strict protection, requiring restoration to occur where damaged by human activity (EU, 2013). However, despite the designation of 53 raised bogs and 55 blanket bogs as Special Areas of Conservation (SACs) the latest Conservation Status Assessment Report published by National Parks and Wildlife Service (NPWS) reported the conservation status of both habitats as Bad: Declining, due to ongoing pressures (NPWS, 2019). The key pressures primarily relate to pressures affecting hydrological conditions required for peat formation to occur. This includes drainage, peat extraction, forestry and burning. These pressures impact on the hydrological supporting conditions within the peatland, particularly water table levels (WTLs) and range of WTL fluctuations.

### RESTORATION

Successful hydrological restoration of peat-accumulating conditions on raised bogs and blanket bogs requires an understanding of the required environmental supporting conditions. Maintaining a stable and high WTL and suitable range of WTL fluctuations is fundamental to controlling ecological conditions (Ellenberg *et al*., 1992; Schouten, 2002; Regan *et al*., 2020). Within relatively intact bogs that are peat-accumulating, the WTL remains close to the ground surface throughout the year, with a limited range of fluctuations (Cushnan, 2018; Regan *et al*., 2020). In bogs that have experienced hydrological disturbance, WTL may drop below critical thresholds for peat-forming vegetation types. Hydrological restoration efforts, including ditch-blocking and berm construction, aims to re-establish a suitable hydrological regime to allow for the re-establishment of peat-accumulating vegetation types and restoration of ecosystem services.

## CASE STUDY

### SITE DESCRIPTION

Fiddandarry (54.149°, -8.927 °) is located within the Ox Mountains Bogs SAC, Co. Sligo, (Figure 2). The SAC is dominated by blanket bog habitat including extensive areas of active blanket bog. Fiddandarry has an average annual rainfall rate of 1,455mm and elevation varies from 170mAMSL to 110mAMSL.

The study site contains parts of two catchments, with the western portion of the site draining into the Gowlan River and the eastern portion of the site draining into the Owenwee River, both of which are tributaries of the River Easky. The vegetation at Fiddandarry is dominated by *Calluna vulgaris*, *Eriophorum angustifolium*, *Eriophorum vaginatum*, *Molinia caerulea* and *Sphagnum* species (Perrin *et al*., 2013). On the flatter areas there are significant areas dominated by Rhynchosporion vegetation and a complex of dystrophic pools and lakes (Perrin *et al*., 2013). The site contains significant areas relatively intact vegetation; however, a series of relatively uniform shallow ditches (approximately 0.5-1m deep) were excavated across several areas of the bog during the early 1980s. Despite the occurrence of drainage, most of the study site is State-owned and as such is subject to low levels of anthropogenic pressure, with limited grazing by sheep from adjacent land parcels and no evidence of recent burning (within the past 20 years, based on aerial imagery).

In early 2021, drainage ditches were blocked with peat dams (Figure 3) constructed using peat extracted from borrow pits adjacent to the ditches. Dams were placed according to topographic slope, with a minimum of 3 dams per 100m on all ditches, increasing to a maximum of 10 dams per 100m on steeper slopes. A small number of ditches adjacent to an area of private ownership were not blocked (Figure 2).

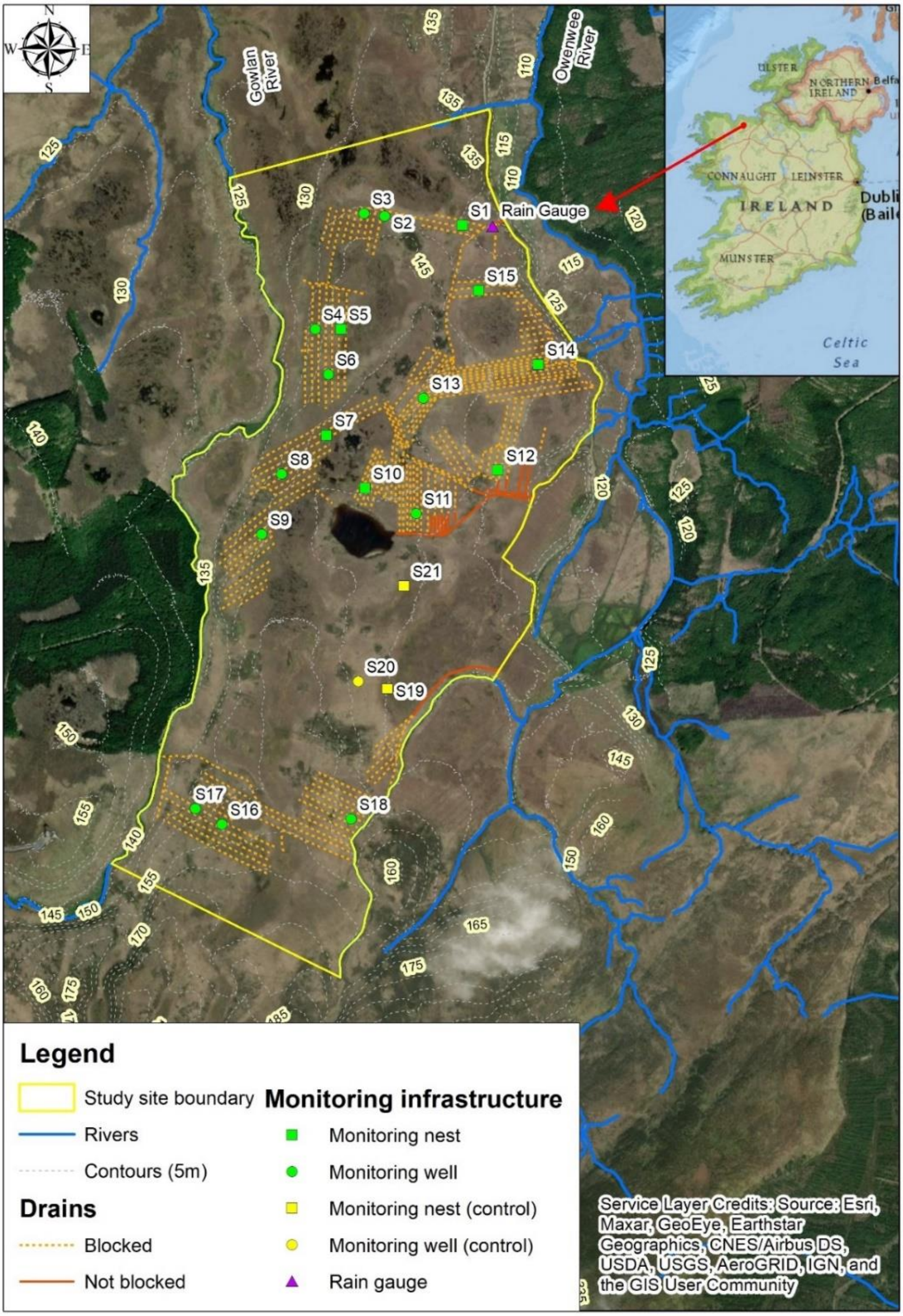



***Figure 2:*** *Location of Fiddandarry study site illustrating position of hydrological monitoring equipment and ditches*

***Figure 3:*** *Example of typical drainage ditch along with peat dams used to block the ditch spaced according to the topographic slope*

## Monitoring

Continuous measurement of precipitation was undertaken using a Solinst RG1 tipping bucket rain gauge (Solinst, ON). Due to instrument failure in November 2020, precipitation records have been supplemented by measurements from a Davis Instruments Vantage Pro-Plus Automatic Weather Station (Davis Instruments, CA) located approximately 2km north of Fiddandarry at Letterunshin Bog. This also enabled rates of potential evapotranspiration (PE) to be calculated at 30-minute intervals throughout the monitoring period.

Twenty-one 32mmID monitoring wells, with 1m screened intervals, were installed across the study site located to capture a representative range of topographic conditions. Eighteen of the monitoring wells were located within drained areas (test wells), while three were placed in an area not influenced by artificial drainage (control wells).

Each monitoring well had an automated pressure transducer (Solinst Junior Edge levelogger® with accuracy ±0.5 cm) (Solinst, ON) to record WTL at 15-minute intervals commencing March 2019. A cap was placed on the well preventing direct ingress of precipitation and the well vented by drilling a hole close to the top of the casing. A Solinst Barologger® (accuracy ±0.5 cm) was installed to measurements of atmospheric pressure to compensate for barometric pressure. Nine monitoring locations also had a deep piezometer, with a 0.5m long screen, installed at the base of peat, permitting manual monitoring of vertical hydraulic gradient. Manual dipping was completed at approximately quarterly intervals to confirm automated readings.

**RESULTS**

Monitoring revealed that summer (April-September) 2022 was the driest summer of the monitoring period with the lowest total inputs of precipitation, fewest wet days (>1mm rainfall) and the highest rate of Potential Evapotranspiration (PE) throughout the monitoring period. Summer 2020 was the second driest summer, with 9% more precipitation, 7% more wet days and total 9% lower PE compared to summer 2022. In contrast, summer 2019 was the wettest summer recorded during the monitoring period with 53% more precipitation, 29% more wet days and 17% lower PE than summer 2022, while summer 2021 had 39% more precipitation, 12% more wet days and 12% lower PE than summer 2022.

Hydrological monitoring revealed WTLs to remain within 70 cm of the ground surface across all locations throughout the entire monitoring period. Nonetheless, notable seasonal differences occurred between locations. During the summer (April-September) monitoring periods, WTLs declined to greater depths than in winter months, with deeper WTLs occurring during summer 2020 and summer 2022 compared to summer 2019 and summer 2021.

Monitoring at the three control wells demonstrates annual variations in WTLs, strongly related to meteorological conditions (Figure 4). The prolonged periods of effective rainfall deficit in April-May 2020 and July-August 2022 result in deeper summer median (S-Med – median of summer (April – September) water table levels), summer D90 (S-D90 calculated as the 10$^{th}$ percentile of water table levels) and summer minimum (S-Min) compared to 2019 or 2021. Overall, results from control wells highlighted the importance of considering meteorological conditions when comparing pre and post-restoration conditions. Meteorological monitoring combined with evidence from control wells, demonstrated that, in the absence of restoration interventions, hydrological responses would be expected to be broadly similar when comparing responses from the same locations in summer 2019 and summer 2021. Furthermore, although more variation exists between summer 2020 and summer 2022, available data suggested that a comparison between statistics such as S-Med between these monitoring periods would be similar, though the more prolonged drought of 2020 indicates S-D90 and S-Min levels would be expected to be deeper in summer 2020 than summer 2022.

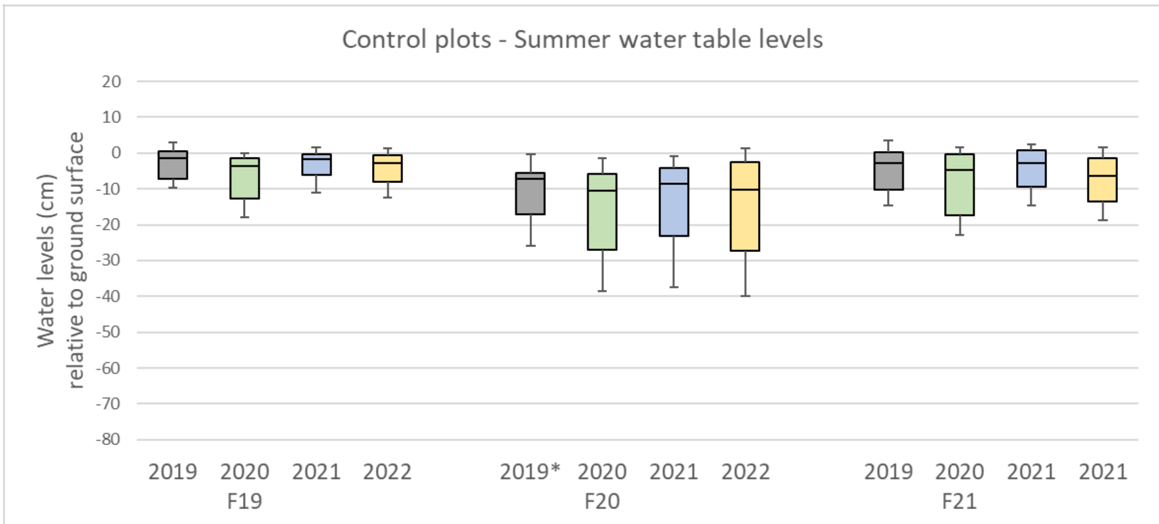
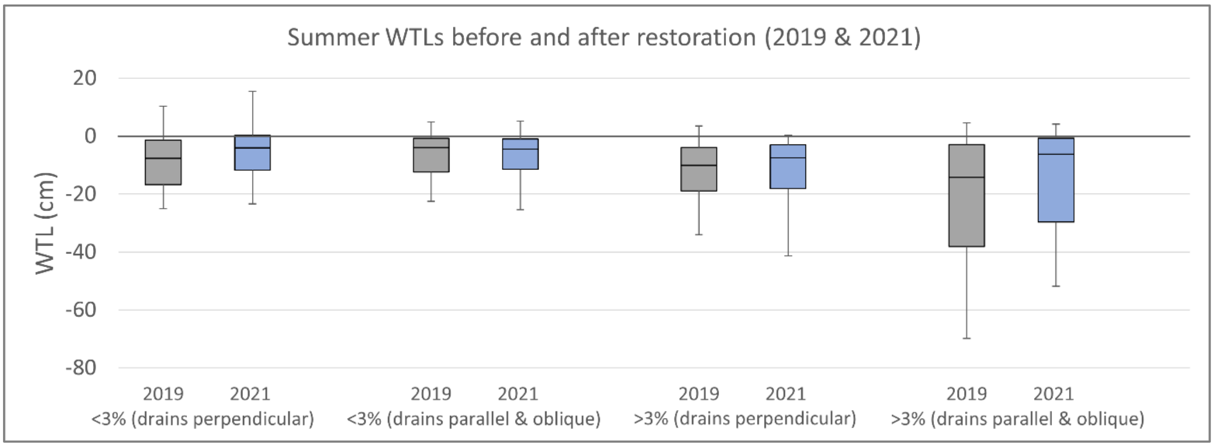



***Figure 4:*** *Box and whisker plot of summer WTLs at three control wells (boxes show S-D10, S-Med and S-D90 levels) illustrating lower water level in summer 2020 and summer 2022 compared to summer 2019 and summer 2021 (*Note monitoring commenced at F20 in July 2019, therefore results for summer 2019 may not accurately represent conditions)*

Box and Whisker plots presented in Figure 5 summarise summer WTLs pre-restoration in summer 2019 and 2020 compared to post-restoration WTLs in summer 2021 and 2022 (note boxes represent S-D10, S-Med, S-D90). Box plots summarise WTLs based on plots on slopes <3% and >3% and whether drain orientation is perpendicular to or parallel and oblique to contours. Results highlight that WTL were shallower prior to ditch-blocking at plots on gentle slopes (<3%), compared to those on steeper slopes, with relatively small increases in S-Med and S-D90 WTLs at plots on slopes <3%. In contrast, there were notable increases in S-Med and S-D90 WTLs at plots on slopes >3%, but only when drain orientation was parallel or oblique to contours.

Comparison of pre-restoration WTLs in summer 2019 to post-restoration WTLs in summer 2021 reveals S-Med levels were higher at 89% of test wells and lower at 11% of test wells after ditch blocking. The mean increase in S-Med was 4 cm (± 6 cm), with an increase ≥5 cm recorded at 39% of test wells. S-D90 levels in summer 2021 were higher at 78% of test wells, equal at 11% of test wells and lower at 11% of test wells (albeit within 2 cm), when compared to 2019 levels. The average increase in S-D90 level was 6 cm (± 5 cm) with an increase ≥5 cm recorded at 50% of test wells. Differences in S-Min levels between 2019 and 2021 proved more variable, with S-Min levels closer to the ground surface at 39% of test wells, equal at 6% and deeper below ground surface at 56% of test wells.

Comparison of pre-restoration WTLs in summer 2020 to post-restoration WTLs in summer 2022 reveals S-Med levels were higher at 83% of test wells, lower at 6% of test wells and equal at 11% after ditch blocking. The mean increase in S-Med was 5 cm (± 4 cm), with an increase ≥5 cm recorded at 56% of test wells. S-D90 levels in 2022 were higher at 94% of test wells and lower at 6% (albeit within 1 cm) compared to 2020. The average increase in S-D90 level was 7 cm (± 6 cm) with an increase ≥5 cm recorded at 56% of test wells. S-Min levels were higher at 83% of test wells, lower at 11% and equal at 6% of test wells in 2022 compared to 2020.



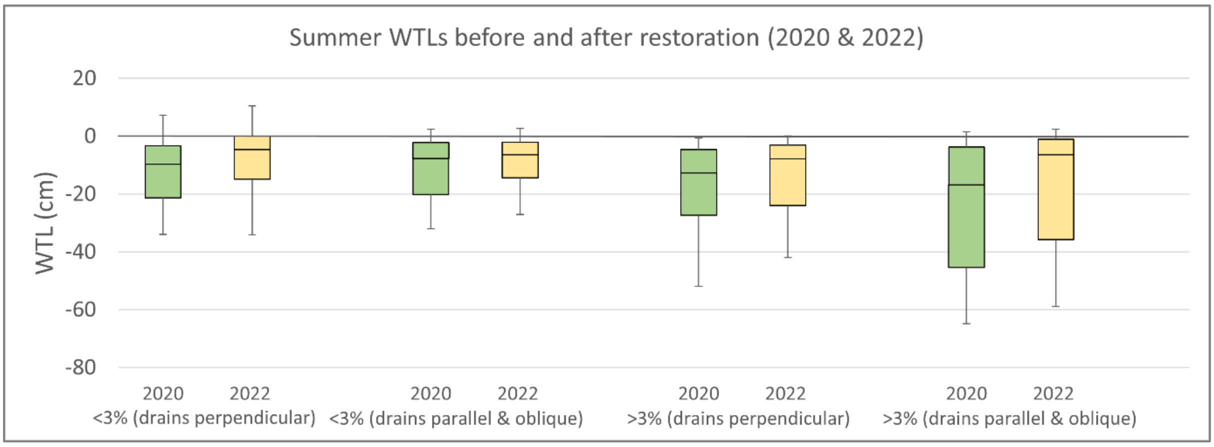




***Figure 5:*** *Box and whisker plots of summer WTLs comparing summer 2019 with summer 2021 (above) and summer 2020 with summer 2022 (below). WTLs have been summarised based on plots on slopes <3% and >3% and whether drain orientation is perpendicular to or parallel and oblique to contours.*

## DISCUSSION

The results from this study show that ditch blocking has caused a rapid change to summer WTLs across the study site within months of ditch blocking across the study site under a wide range of topographic conditions. This contrasts with the findings from other studies in the UK, such as Wilson *et al.* (2010) who reported a very gradual recovery of WTLs following ditch blocking in a Welsh upland blanket bog, with at least a year before impacts were observed.

Furthermore, while several studies of ditch-blocking on blanket bogs in the UK have reported only modest increases (~2cm) in WTL following ditch blocking (e.g., Holden *et al.*, 2016; Wilson *et al.*, 2010; Williamson *et al.*, 2017), this study found significant increases (≥5 cm) in S-Med and S-D90 occurred at test wells located on a wide range of topographic slopes (1.7% to 12.5%), with the largest increases in WTL were reported at wells located on the steepest slopes of all monitoring wells (≥10%). However, despite the significant increases in WTL levels at locates on steep slopes, S-D90 levels after restoration remain deepest at these monitoring wells, highlighting the importance of topographic factors in controlling the hydrology of blanket bogs, as noted by studies such as Holden *et al.* (2011).

The largest increases in in WTL levels were reported at locations in the immediate vicinity of drains, with gentle surface slope (<3%) or where ditches are oblique to or run parallel to contour lines of the slope, even where slopes are moderate to steep (i.e., >3 %). This demonstrates that beyond the immediate influence of the drain (within approximately 5 m), shallow ditches running perpendicular to contour lines have a limited impact on WTL, particularly as surface slope increases above 3% and contributing catchment area decreases.

Increases in S-Med and S-D90 values of more than 2 cm were only reported at test wells with ditches running perpendicular to contour lines if surface slopes were <3 %, or where slopes are steeper than 3 % and there is a large contributing catchment area (≥0.5 ha). Other than well F14 which is located within 2 m of a drain, the largest increase in S-Med and S-D90 where ditches ran perpendicular to contour lines was in an area of gentle surface slope (<2%) at test well F10.

## CONCLUSIONS

This study has revealed that ditch blocking in a lowland blanket bog led to a rapid change in hydrological conditions within less than one year, including shallower and more stable WTLs. The findings contrast with those of several similar studies of ditch blocking in blanket bogs in the UK, where only modest increases in WTL have been reported and a slow response reported. Results highlight the importance of topographic controls on WTL fluctuations and some of the key topographic factors that will influence the extent of impact of a drainage ditch on water level regimes. Furthermore, while studies of upland blanket bogs from the UK provide important principles that can be applied to Irish bogs, these may not be directly applicable to lowland blanket bogs.

Overall, the significant hydrological response suggests drained areas of drained lowland blanket bog can be successfully rewet through ditch blocking programmes. However, in designing blanket bog restoration projects, it is important to be cognisant that different ditches will have a different level of influence on peatland hydrology and prioritise accordingly.

## ACKNOWLEDGEMNENTS

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# SESSION VI

# With Geothermal Power comes Geothermal Responsibility!

**Harlin, K.** *Geosyntec Consultants Ltd.*

"*Hydrogeologists make excellent Geothermal Geologists*". That's the message being echoed around Geosyntec Consultants after a successful recent foray into the world of geothermal consultancy. In fact, as hydros and contaminated land specialists, we can offer a more holistic approach to the vital design phase of these exciting projects.

The 23rd of February 2024 marked the day that the final length of geothermal collector was installed at a pharmaceutical research site near Liverpool in the UK. The geothermal system was designed to provide the entire heating and cooling energy requirements for a new state of the art office building with ambitious performance targets.

This talk will not only look at the steps involved in the familiar feasibility and sizing aspects of the system but will also focus on the often-overlooked risks that these systems can pose to sensitive environmental receptors if left unchecked. In summary, many potentially overlooked hazards such as ground gas generation, settlement issues, the disturbance of temperature sensitive ecological environments and even the mobilisation of legacy contaminants should be considered before we race towards exciting and economically enticing greener energies.

# THE GEOCHEMISTRY OF URBAN KARST

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## ABSTRACT

*The complex network of subsurface infrastructure in urban environments has characteristics similar to those of carbonate karst regions. Numerous authors over the past 25 years have referred to this system of pipes, human produced holes, and cavities as "urban karst." Subsurface pipes in urban regions transport fluids including municipal water supply, storm overflow runoff, and domestic sewage that can mix with natural groundwater. The storm waters contain impurities derived from contact with buildings, other above ground infrastructure, and impervious surfaces, such as roadways, parking lots, and sidewalks. Herein we review the nature of urban karst environments as it reflects on the location, age, and infrastructure of the urban area. Finally, we present geochemical data from urban karst waters from Columbus, Ohio, USA and compare our urban karst data to those from local city river water in order to quantify possible impact of urban karst waters on surface water quality.*

**Key words:** *urban karst, water quality, storm runoff*

## INTRODUCTION

The analogy between the subsurface karst environment and the urban subsurface was suggested as early as 2003–2005 (Sharp et al., 2003; Garcia-Fresca and Sharp, 2005), but a major description of "urban karst" was not provided for another decade (Kaushal and Belt, 2015). A review of the importance of stormwater infiltration in landscapes dominated by impervious surfaces into urban groundwater was published two years later (Bonneau et al., 2017). One of the major anthropogenic effects during urbanization is the alteration of the shallow land sub-surface (Lyons and Harmon, 2012). The urban subsurface consists of many characteristics that can alter water flow paths and increase permeability. These include anthropogenically altered soil and constructed trenches for telecommunication, gas, and other utilities. These disturbed, heterogeneous soils can lead to the development of preferential flow paths, and higher infiltration rates. The trenches are usually underlain with sand and gravel with very different porosities and permeabilities than the surrounding materials, producing different hydraulic conductivities. This, too, leads to the development of preferential flow paths and exfiltration through markedly different head variations unrelated to the locations of surface infiltration (Shepley et al., 2019).

The urban subsurface also consists of a dense, complex network of pipes and conduits carrying various types of water. These include pipes delivering municipal water, pipes collecting domestic waste, and pipes associated with storm water overflow. All these pipes can leak, and the leaked fluid can first infiltrate into the sub-surface soils and eventually into the groundwater aquifer. This leakage will vary with city and infrastructure age, rates of infrastructure deterioration, and maintenance. Poor construction, bad design, mismanagement, loading by urban vehicular traffic and construction, and available finances can also affect this water loss through time (Dixon et al., 2018). Degradation of concrete by fracturing resulting from freeze-thaw activity and chemical weathering can also affect the integrity of the materials and increase leakage over time. Even impervious surface materials are susceptible to these processes, and the infiltration of water through them has been termed secondary permeability (Sharp et al., 2003). Millions of cubic meters of water are lost annually from water utilities and sewage collection pipes in urban areas (D'Aniello et al., 2021). D'Aniello et al. (2021) emphasize that the fate of this leaked water is not well known. Not only is there lack of information on urban karst water transport rate and ultimate flux into the local surface water, but also less has been published on the biogeochemistry of these waters. Clearly such factors as local climate, the age of the urban area, the surface and sub-surface infrastructure make-up and maintenance, the human population density, and the ratio of impervious area to greenspace within the watershed, will all influence the geochemistry of these urban karst waters. For example, recent work by Flint et al. (2023) estimated that 0.7–2.6 kt of phosphate-P is lost from water pipe leakage annually in the USA. Losses of other chemicals, and from other urban karst sources, such as sewage and storm runoff from impervious surfaces, are much less well known.

In this paper we present some preliminary findings on the geochemistry of urban karst waters draining an urban region in Columbus, Ohio, USA and focus on the waters entering the Olentangy River on the campus of The Ohio State University. We will compare these urban karst waters to other types of waters found in the city of Columbus to establish the sources of chemicals to the sub-surface samples.

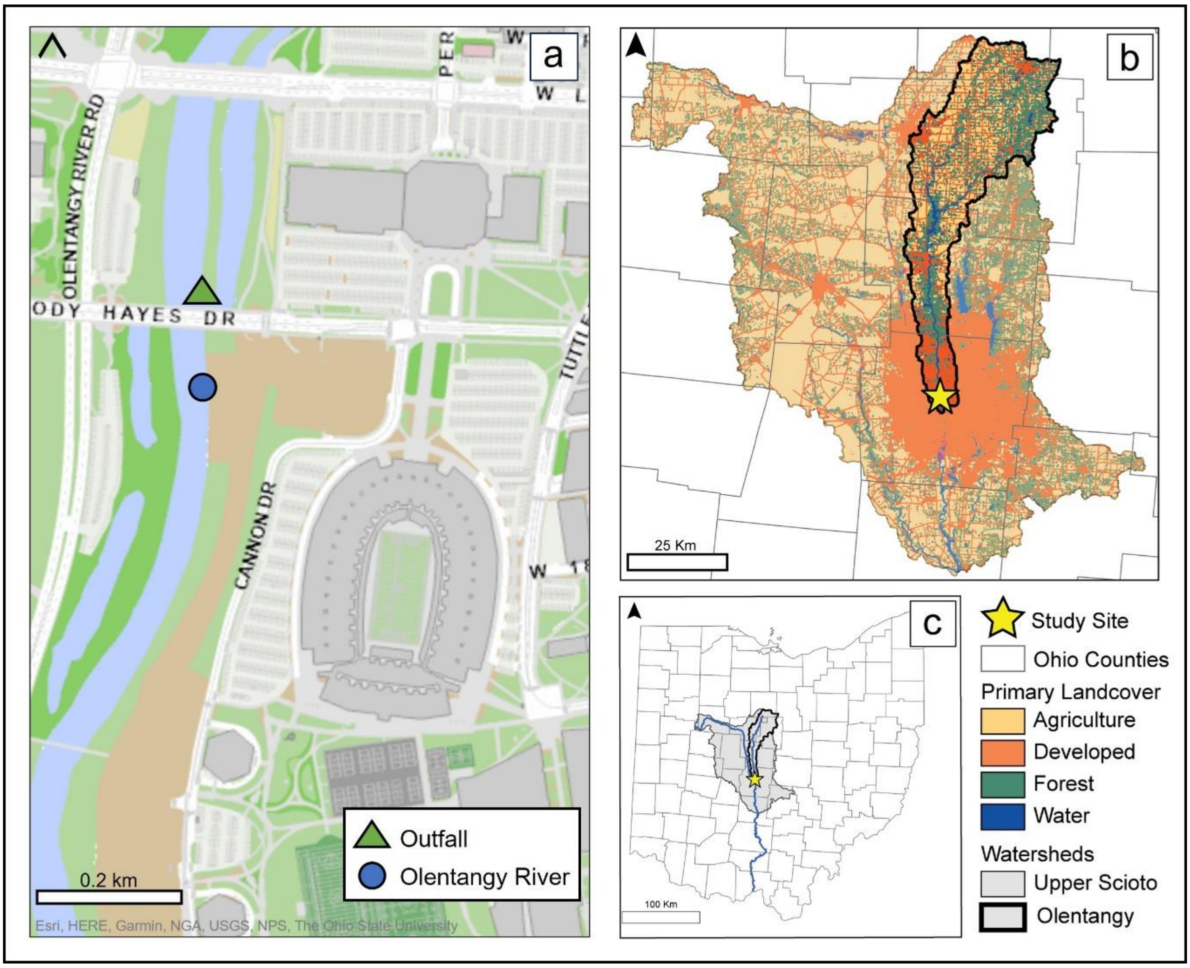
## SAMPLING LOCATIONS

Columbus, Ohio is currently the 14$^{th}$ largest city in the USA with a population of 909,676. The main campus of The Ohio State University is located in north-central Columbus and abuts the Olentangy River, a major tributary that joins the Scioto River in downtown Columbus (Map 1). The upper portion of the Olentangy watershed is dominated by agricultural land use. As the river flows south past the city of Delaware it encounters the suburbs of Columbus in both Delaware and Franklin counties before entering Columbus proper. In the most suburbanized and urbanized areas of the watershed, outfalls transport urban karst waters directly into the river. Based on our own observations, the outfall volumes are probably dominated by storm overflow waters, as the quality and quantity of flow wax and wane with precipitation events. From November 2021 through November 2022, we sampled one of the larger outfalls entering from the east of the river and underlying a road on the Ohio State campus. The watershed of this outfall extends eastward, across High Street (the major N-S thoroughfare in the city and the eastward extent of the university campus) into the city proper, for another estimated ~1 km. Twenty-nine samples were taken during this period, during both 'low flow' (less than 50 percentile flow) and 'high flow" (greater than 50 percentile) events. Two other outfalls north of campus were sampled in September 2023 during 'low' flow conditions. River water samples were also collected when the outfall water samples were obtained.

## METHODS

All water samples were collected using a precleaned 1 L polyethylene bottle attached to a PVC pipe. The sampler was rinsed with sample water prior to decanting sample water into a precleaned 250 ml polyethylene container. This sample container was rinsed 3 times with sample water before the final water aliquot was obtained. The samples were returned to our laboratory on campus and filtered using a new, polypropylene syringe with a 0.45$\mu$m pore-size inline cellulose acetate filter attached. Aliquots were filtered directly into a 60 ml bottle that had been rinsed with deionized water (18 M$\Omega$) for aliquots to be utilized for major anion and nutrient analyses, and into a 10% HCl rinsed 60 ml bottle for aliquots to be used for major cation analyses. The 60 ml bottles were pre-rinsed with filtered sample immediately prior to final sample addition. At the sampling location, another water sample was decanted, leaving no headspace, into a 20 ml vial for water stable isotope analysis. All the samples were stored at ~4 C prior to analysis.

Major cation and anion analyses were accomplished using a Dionex ion chromatograph, nutrient analysis was completed using a Skalar nutrient analyzer, and water stable isotopes were determined using a Picarro Cavity Ring-Down Spectrometer. Processing and field blanks were also analyzed for quality control. The accuracy of all measurements was 10% or better; precision was 1% or less. Details of water processing procedures and precision and accuracy determinations can be found in Lyons et al. (2021).




***Map 1:*** *Study site location maps showing (a) The Ohio State University and the outfall and river sampling locations; (b) the upper Scioto River and Olentangy River watersheds; and (c) the state of Ohio, its 88 counties, and the upper Scioto River watershed location in central Ohio (Dewitz, 2021; USGS, 2011, 2023).*

## RESULTS AND DISCUSSION

The mean dissolved concentrations of Cl, $NO_3$, Ca, $PO_4$, $H_4SiO_4$ and F from several types of urban waters in the Ohio State area are given in Table 1. Several important observations and conclusions come from viewing these data. The highest mean Cl values are in the urban karst waters associated with the Ohio State campus. We interpret that these high values are sourced primarily from roadway and sidewalk deicing salts used to melt snow and ice during the winter period. Gardner and Carey (2004) demonstrated that motorway runoff in Columbus continues to have high Na and Cl concentrations associated with deicing salts in the summer and autumn months, as it is continually leached from cracks and small fissures in the concrete and asphalt of the roadway surfaces. The much lower solute concentrations in the Como Park and Northmoor Park outfalls probably reflect the timing of collection (late September during low water flows), and the fact that these outfalls drain watersheds with less vehicular traffic and lower seasonal deicing salt application. Even though the urban karst waters are a source of $NO_3$ to the river system, the highest values of $NO_3$ are found in the river itself. These high riverine solute concentrations are associated with the agricultural influence of the northern portion of the Olentangy watershed, which is dominated by row crop land use. The highest $PO_4$ concentrations are associated with the municipal water. Interestingly, the highest dissolved Si and Ca concentrations were found in the urban karst waters. This strongly suggests that the chemical weathering of both surface and sub-surface infrastructure. The dissolution of concrete and other masonry materials has been demonstrated to be important in other urban areas (Kaushal et al., 2020) and we suggest that it is a major control on water geochemistry in urban karst in Columbus. The Si/Ca molar ratio of the urban karst water is higher than the river water value, implying either that there is a greater source of dissolvable Si in the urban sub-surface or that the river is more influenced by the carbonate lithology that underlies a portion of the Olentangy watershed.

The highest F concentration is in the municipal tap water where, in Columbus, F is added to during treatment prior to potable water distribution. The higher F values, compared to the more "natural" concentrations in the river water, act as a significant source tracer of leakage (or direct input) of municipal water supply. The higher F concentration in the urban karst water suggests to us that these waters contain leaked municipal water because the F concentration is 36X higher than precipitation (Table 1).

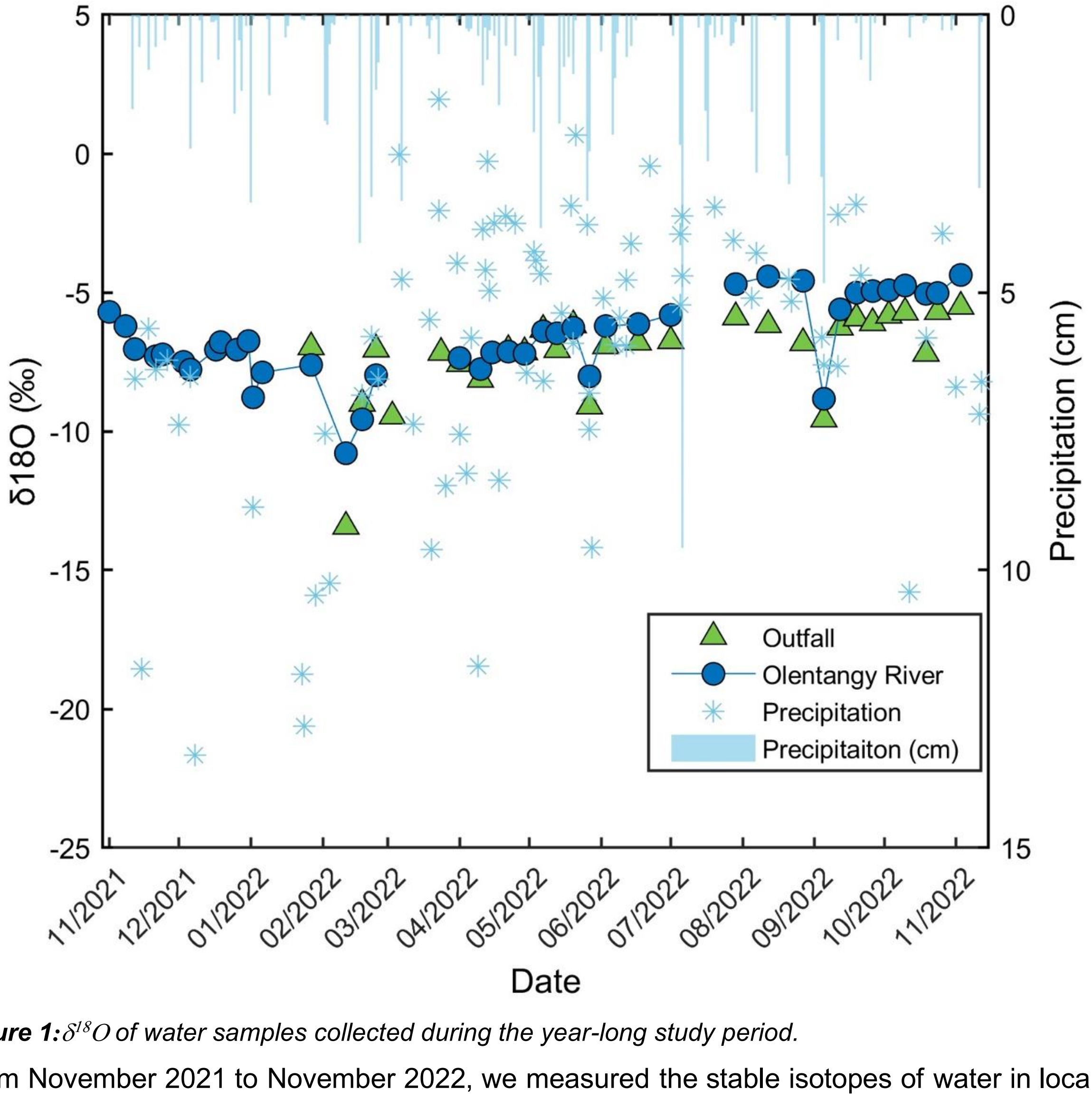



***Figure 1:*** *$\delta^{18}O$ of water samples collected during the year-long study period.*

From November 2021 to November 2022, we measured the stable isotopes of water in local precipitation, the Olentangy River, and from the outfall of the urban karst on the Ohio State campus (Figure 1). This series also shows the timing and amount of precipitation during our sampling period. We have assumed that the times when the urban karst water $\delta^{18}$O values are similar to the precipitation values that the major source of urban karst water is from event water and hence a storm overflow source. However, there are times when this is not the case (Figure 1). There are numerous occasions, especially during Spring into Autumn when the precipitation is more enriched compared to the urban karst waters, and there are also times when the opposite is true, where precipitation is more depleted compared to the urban karst water. These times include periods in the Winter, early Spring and later in the Autumn (Figure 1). These differences between the isotopic signature of the event water and the urban karst water suggests that either 1) there are other, unknown sources of water entering the sub-surface system, or that 2) there are waters in the system with longer residence times (i.e., different, perhaps longer path lines, or areas where water can be stored for periods of time) that may represent mixtures of previous precipitation events. Clearly the amount and frequency of local events help to explain the differences between the two water types, with higher amounts and frequencies leading to similar isotopic values of urban karst waters.

As acknowledged above, there is also municipal water entering the system. Previous work by Leslie et al. (2014) demonstrated that monthly and seasonal climate conditions can greatly affect the tap water isotopic signature, with lower-than-average rainfall conditions within the watershed leading to a lag time of water moving through the municipal distribution infrastructure, i.e., with tap water in the Autumn looking like Spring precipitation. The general trend in isotopic composition of the urban karst waters looks much like the river trend which is a mixture of many precipitation events where the isotopic signal of individual events is damped (Smith et al., 2024). Research on the isotopic composition of urban river baseflow in Victoria, Australia has shown that urban water can have variable sources and pathways compared to more forested reaches, implying that these isotopic variations reflect the direct influence of urbanization on the hydrogeology of the system (Bonneau et al., 2018).

The geochemical data presented herein strongly indicate that the urban karst waters underlying the Ohio State campus are a mix of precipitation that has interacted with impervious surfaces, sub-surface infrastructure, and municipal water supply. In future work, we hope to be able to continue to quantify and qualify input from these different sources.

***Table 1:*** *Mean concentrations for urban water types in the Ohio State University environs, Columbus Ohio, USA (all values in mmol/L except F which is in $\mu$mol/L)*

| **Location** | **$Cl^-$** | **$NO_3^-$** | **$Ca^{2+}$** | **$PO_4^{3-}$** | **$H_4SiO_4$** | **F** |
|---|---|---|---|---|---|---|
| Large urban karst runoff, Ohio State campus | 9. 3.86 | 10. 0.04 | 11. 2.24 | 12. 0.001 | 13. 0.15 | 14. 18 |
| Outfall at Como Park[1] | 16. 0.05 | 17. 0.03 | 18. 0.38 | 19. — | 20. — | 21. — |
| Outfall at Northmoor Park[1] | 23. 0.09 | 24. 0.04 | 25. 0.31 | 26. — | 27. — | 28. — |
| Columbus municipal water supply[2] | 30. 0.94 | 31. 0.06 | 32. 0.80 | 33. 0.009 | 34. 0.04 | 35. 44 |
| Olentangy River at Woody Hayes Drive | 37. 1.52 | 38. 0.125 | 39. 1.42 | 40. | 41. 0.001 | 42. 11 |
| Precipitation[3] | 44. 0.013 | 45. 0.021 | 46. 0.032 | 47. <0.003 | 48. — | 49. 0.05 |

[1] Based on one sample from October 2023.

[2] n=28 samples collected from drinking fountains and bathroom faucets across campus

[3] n= 170 to 349 samples (dependent upon analyte) collected in an open-bucket collector in the Clintonville neighbourhood, 5 km north of campus

## ACKNOWLEDGEMENTS

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# WELLS AND WELLBEING: WRITING A BOOK ABOUT HOLY WELLS IN IRELAND

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**ABSTRACT**

*This paper summarises some of the main findings of a five-year investigation into the hydrogeology of Irish holy wells, and then talks about the subsequent challenges in writing a book about this research, a book targeted at a non-technical as well as a hydrogeologist readership. The aim of the book is to promote a greater understanding of the sources and properties of the water that feed these wells and springs, and to stimulate a wider interest in groundwater science. The book "Wells and Wellbeing: The Hydrogeology of Irish Holy Wells" was published by Geological Survey Ireland in November 2023.*
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**Key words:** *Holy wells and springs, groundwater chemistry, health.*

## INTRODUCTION

Holy wells have been features of our Irish landscape and culture for many centuries (and probably thousands of years in some cases). Mapping in the 19$^{th}$ century recorded around 3,000 of these wells, many of which are still visited today by individuals or groups of pilgrims, especially on the pattern days. Holy wells have been described previously as "the people's spas" (Foley, 2010) and so can be regarded as a type of nature-based solution, one that links groundwater to human health and wellbeing.

The first part of this paper summarises the findings of a five-year research project into the hydrogeology of Irish holy wells. The second part deals with the challenges of writing a book about this research, a book aimed at a non-technical as well as a scientific readership.

## THE RSEARCH

The main elements of the research were an analysis of the distribution of holy well settings across the country, field surveys of selected holy wells and the collection and analysis of water samples.

### DISTRIBUTION OF HOLY WELLS

The research commenced with an investigation of the distribution of holy wells according to their location, elevation, physiography, bedrock geology, lithology, aquifer class and groundwater vulnerability. This analysis was performed with the geographical information system ArcGIS. A National Monuments Service database of holy wells (which included 2,676 wells with locational details) and Geological Survey Ireland map layers were used in this exercise.

As an example of results of the GIS analysis, Figure 1 shows the numbers of wells within six main lithological groupings, together with the percent wells versus percent area represented by each lithology. The lithological groupings were based on the 27 groundwater Rock Unit Groups (RUGs) identified by Geological Survey Ireland, plus sands and gravels, and followed the earlier example of groupings in Tedd *et al*. (2017). It can be seen that holy wells are found in each of the main groups in approximate proportion to the areas covered by these lithologies. There are slightly higher frequencies in the pure limestone grouping, which is unsurprising because pure limestones provide many of the country's best aquifers. But it is also clear that holy wells are common in poorer aquifer lithologies such as metamorphic rocks. Indeed, it was found that 68% of holy wells occur within poorly productive aquifers (i.e. Pl, Pu and Ll aquifer classes – see Working Group on Groundwater, 2005) that occupy about 72% of the country.

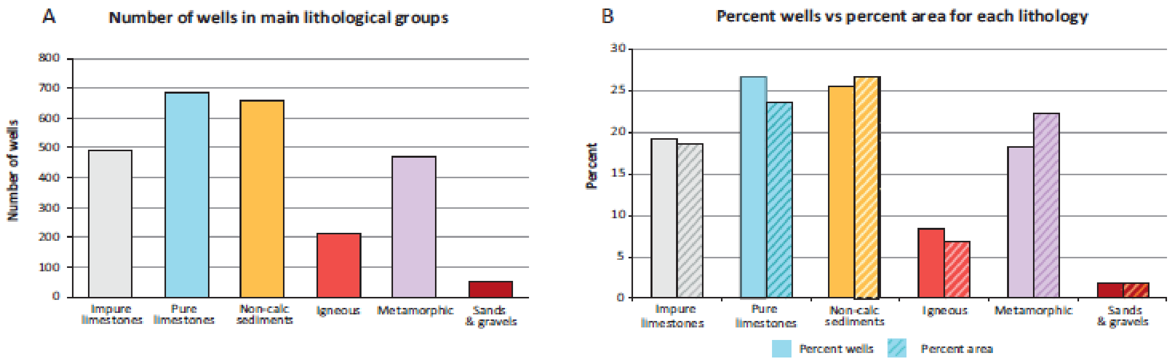


***Figure 1:*** *(A) Number of holy wells and (B) percent wells versus percent area for each lithological group*

One of the interesting findings was that holy wells were much more frequent within the higher groundwater vulnerability areas, with 74% of wells falling into the X and E Extreme and H categories (Figure 2).

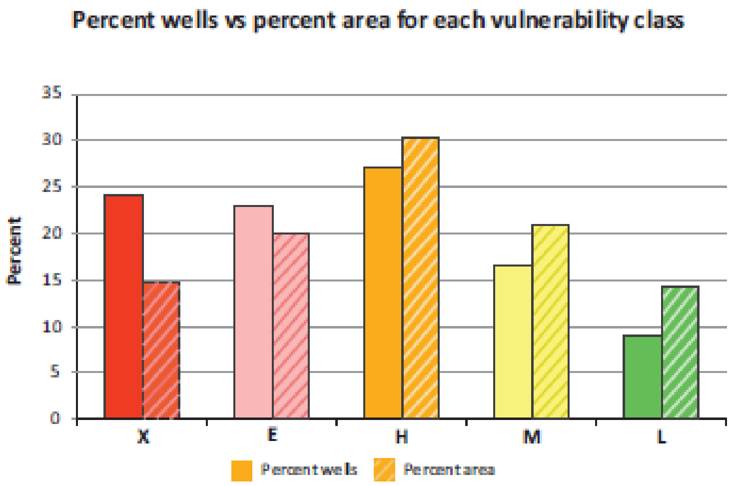


***Figure 2:*** *Percent wells versus percent area in each groundwater vulnerability category*

The GIS analyses were followed up by field surveys of 215 holy wells (and five spa wells). These included wells in all 26 traditional counties of the Republic of Ireland, and represented all of the main physiographic, geological and hydrogeological settings. A short report was prepared on each site, with details of location, accessibility, well dimensions, water levels, topography, geology, hydrogeology, water electrical conductivity, water temperature, pH, water sample number (if sampled), weather conditions, reputed cures, etc. Maps of location, subsoils, bedrock geology, aquifer class and groundwater vulnerability were prepared using the GSI Groundwater Viewer.

The field surveys confirmed that the majority of holy wells were based around shallow springs and seeps, often in areas of Extreme or High groundwater vulnerability. There are a few instances of large karst limestone springs designated as holy wells, such as Tobernalt near Carraroe in Co Sligo and Ogulla well at Tulsk in Co Roscommon. Holy wells that tap deep confined aquifers are rare but include St Gorman's well near Enfield, in Co Meath, and St Brigid's well at Shangarry in Newcastle West, Co Limerick. These two wells have reputations as warm water wells (especially St Gorman's well), and both tap Carboniferous limestone aquifers.

WATER CHEMISTRY

A total of 167 of the 215 surveyed holy wells were sampled for their water chemistries. Four of these wells were selected for regular monitoring over a two-year period, to see if there were seasonal variations in chemistry. Samples were tested for major ions, minor ions and trace elements, giving a total of some 60 chemical parameters. In addition, water electrical conductivity (EC), temperature and pH which were determined on site using a hand-held meter. The research thus yielded a comprehensive geochemical database.

The chemical analyses showed that the water chemistry of holy wells (like that of other groundwaters) is strongly influenced by aquifer lithology. As an example, Figure 3 shows the cumulative frequency distribution of calcium ion for the main lithological groups (also including a seventh group, mixed bedrock and gravel). Clear differences are evident between the samples from wells in carbonate lithologies (pure and impure limestones, sands and gravels and mixed groups) and the other lithologies (non-calcareous sedimentary, igneous and metamorphic).

As well as lithological influences, it was also found that wells closer to the sea had elevated sodium and chloride concentrations compared to non-coastal wells. This again is unsurprising, as rainfall and hence groundwater recharge in coastal areas may be affected by sea spray.

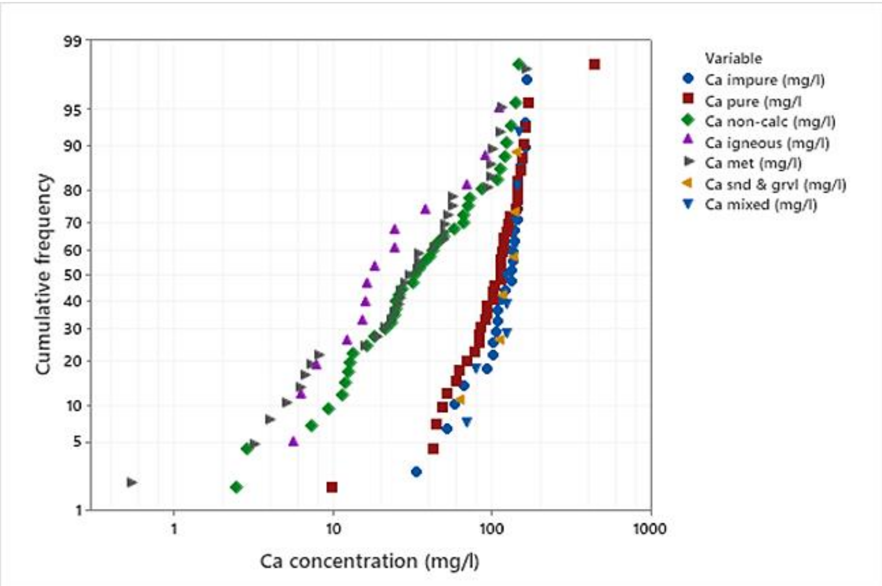


***Figure 3:*** *Cumulative probability diagram for calcium ion*

Nitrate results are important when assessing potential anthropogenic impacts on groundwater chemistry. Whilst there were only a few wells where nitrate levels exceeded the drinking water standard of 11.3 mg/l (as N), water samples were above the background level of 2 mg/l as N (defined in Tedd *et al.*, 2017) in 52% of wells. There was not a strong correlation between nitrate values and groundwater vulnerability class (Table 1). The mean nitrate values were above the background level in all vulnerability categories, and statistical analysis (using the one way analysis of variance, or ANOVA, test, on log-transformed data) showed the only significant difference to be between the means in the High and Low vulnerability categories (which were the categories with the highest and lowest mean nitrate concentrations, respectively).

***Table 1:*** *Comparison of nitrate values with groundwater vulnerability class.*

| | X | E | H | M | L |
|---|---|---|---|---|---|
| Number of well samples | 51 | 30 | 48 | 27 | 11 |
| Median $NO_3$ (mg/l as N) | 1.6 | 2.1 | 3.3 | 2.6 | 0.8 |
| Mean $NO_3$ (mg/l as N) | 3.9 | 2.9 | 4.1 | 2.9 | 2.6 |
| Nr samples with $NO_3 > 2.0$ mg/l | 19 | 15 | 32 | 17 | 4 |

At first sight, the general lack of correlation between nitrate distributions and the geological classification of groundwater vulnerability might seem surprising. However, it is important to bear in mind that these shallow spring wells may be impacted by local discharges or runoff that can bypass subsurface geological pathways. In this respect, a study of water quality in private wells in four areas in Ireland found that the incidences of pollution (in that case faecal bacteria) were as high or even higher in the one area with Low vulnerability compared to the other three areas which were characterised by High or Extreme groundwater vulnerability (Hynds *et al.*, 2012).

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HEALING REPUTATIONS

Many sacred springs and wells across the world have reputations for healing a range of ailments, with reports of cures for sore eyes being particularly common (Bord and Bord, 1985; Varner, 2009; Ray, 2020). In this research, some evidence for healing reputations was discovered for 57% of the wells surveyed (but it should be appreciated that the “evidence” included oral and internet sources as well as peer-reviewed publications, so the figures are not necessarily complete or fully reliable). In line with experience elsewhere, eye cures were the most frequently reported (at 27% of surveyed wells), followed by general or unspecified cures (14% of wells), rheumatism and similar body aches (11%) and toothache (8%); see Figure 4).

Statistical tests did not show any significant differences in the concentrations of most chemical parameters between wells having a particular healing reputation and the other wells. However, in wells with a reputation for treating eye ailments, it was found that median sodium and chloride concentrations were higher than those in the remaining well samples. A likely explanation is that the frequency of “eye wells” was found to be higher near the coast.

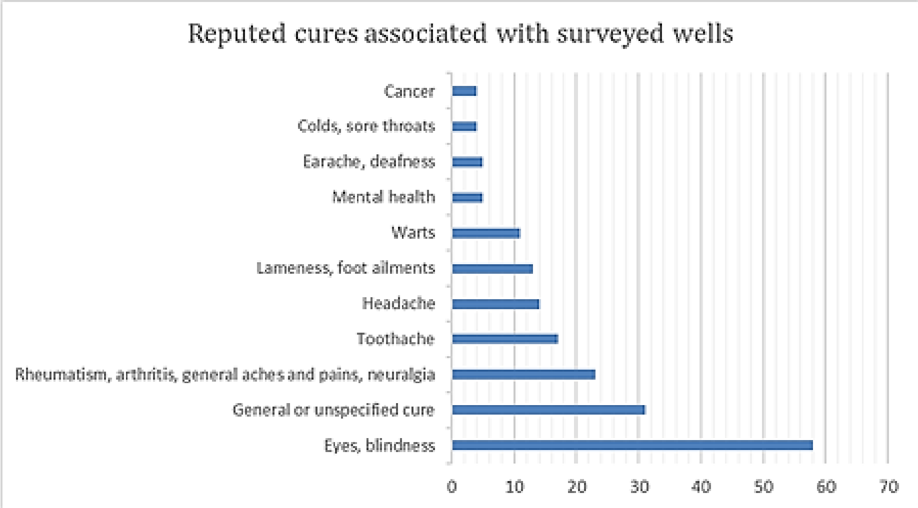


***Figure 4:*** *Reputed cures for the 215 surveyed wells*

In considering perceived health benefits, we should recognise that the attractive landscape settings where many holy wells are found may have some therapeutic value, and that the personal beliefs of visitors to the wells are also important.

## THE BOOK

The book "Wells and Wellbeing: The Hydrogeology of Irish Holy Wells" was published by Geological Survey Ireland in November 2023 (Figure 5).

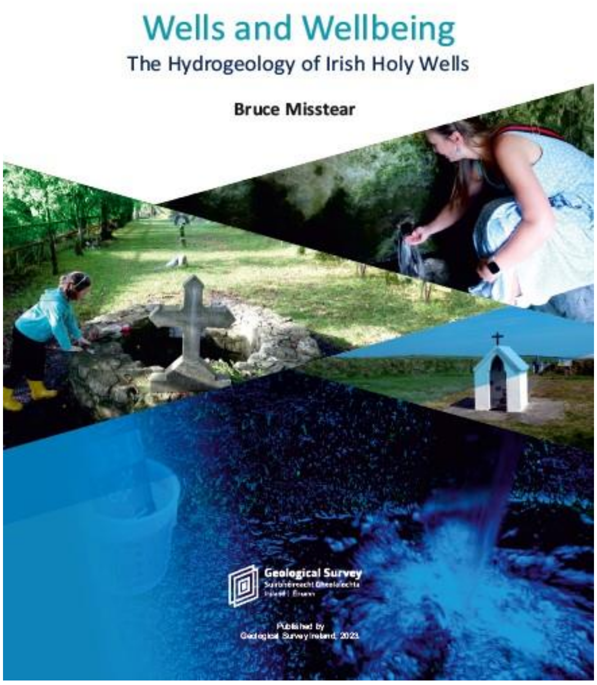


***Figure 5:*** *The book cover*

The aims in writing the book were twofold: a) to publish a detailed account of the research findings, and b) to increase the awareness about holy wells and groundwater issues more generally. The ambition was therefore to appeal to a non-technical as well as a technical readership.

The book is arranged in four parts:

Part 1: Introduction to Wells and Holy Wells
Part 2: The Hydrogeology of Irish Holy Wells
Part 3: The Water Chemistry of Irish Holy Wells
Part 4: Preserving Holy Wells for Future Generations

Although it is hoped that readers from all backgrounds will find material of interest to them in each part of the book, the more technical information is contained in Parts 2 and 3, which therefore may be of most interest to hydrogeologists. Part 2 describes the distribution of holy wells in their different physiographical and hydrogeological settings, and then provides accounts of 20 holy wells as examples, plus five spa wells. Part 3 presents the results of the water chemistry analyses, before going on to consider the potential links between the water characteristics and human health and wellbeing.

To improve readability, the use of technical jargon is minimised (but not avoided altogether). Basic concepts are explained with the aid of text boxes (there are 21 of these distributed throughout the book). The boxes address topics such as groundwater flow, aquifers, aquifer classification in Ireland, groundwater vulnerability, composition of groundwater and chemical sampling and analysis procedures. The presentation of boxes on groundwater concepts was aided by the availability of illustrations from sources such as USGS, UK Groundwater Forum and WFD Visual. There are also text boxes that deal with folklore, including brief accounts of the lives of saints Brigid and Colmcille, the traditions surrounding the placing of rags and votive offerings at holy wells and the useful information that can be gained from the 1930's Schools Folklore Collection (Irish Folklore Commission, 1937-38). One box looks at the many stories about wells having moved to a new location after being "offended" (for example by being used for domestic purposes) and considers if there could be geological explanations for such stories.

Again, to aid readability, the conventional scientific publication approach to referencing is avoided. Authors' names are not included in the text, but rather numbered endnotes are used instead (there are 280 Notes included after the main text). A full bibliography is given at the end.

Illustrations are key features of any hydrogeology (or indeed popular science) publication. In this book, there are many maps and graphs (prepared with the considerable help and expertise of the Cartographic team at GSI) plus around 200 photos. Examples of the types of photos are shown in Figure 6. Although these examples are not taken from the book, they do give some idea of the diversity of holy well settings.

A

B

C

D

***Figure 6:*** *Photos of holy wells. (A): St John's well on the side of Musheramore Mountain, Co Cork (Devonian Old Red Sandstone aquifer); (B): Ladywell, an example of a holy well in an urban setting, Dundalk, Co Louth (the bedrock is Silurian Clontail Formation); (C) Tobar Rí an Dhomhnaigh (Our Lord's well of the Sabbath), Kilgeever, Co Mayo, one of many holy wells located inside a graveyard (Silurian Lough Nacorra Formation); (D): St Colmcille's well on the shoreline at Doonierin, Co Sligo (Dinantian Dartry Limestone Formation). Photos by Bruce Misstear*

Finally, many holy wells have been covered over or otherwise destroyed over the years. In view of their continuing cultural relevance, it is important to increase efforts to preserve them for future generations. Individual landowners and local volunteer groups play a key role in protecting our heritage, as do local authority heritage officers and the Heritage Council. As hydrogeologists, we can help by investigating and documenting holy wells, and by promoting the designation of selected holy wells as County Geological Sites (and potentially National Heritage Areas). We can also help raise awareness about possible water quality issues when people drink water from unprotected water sources.

## ACKNOWLEDGEMENTS

The contributions of the following people to the research and book are gratefully acknowledged: Laurence Gill, Cora McKenna and Niamh Harty (Trinity College Dublin); Ronan Foley (Maynooth University); Taly Hunter Williams and Eddie McMonagle (Geological Survey Ireland); Gillian Misstear.

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# POSTERS

# REWET: HYDROLOGIC IMPACTS OF WATER TABLE MANAGEMENT ON GRASSLAND PEAT SOILS

***Hilary Pierce,*** *University of Galway*

# REWET: Hydrologic impacts of water table management on grassland peat soils

Hilary Pierce[1] (h.pierce1@universityofgalway.ie), Dave O'Leary[2], Eve Daly[1], Owen Fenton[3], Asaf Shnel[2], Mark G. Healy[4], Patrick Tuohy[2]
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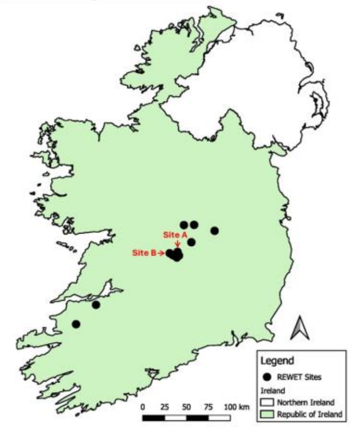
[2]Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork
[3]Teagasc, Environment Research Centre, Johnstown Castle, Co. Wexford
[4]Civil Engineering and Ryan Institute, College of Science and Engineering, University of Galway

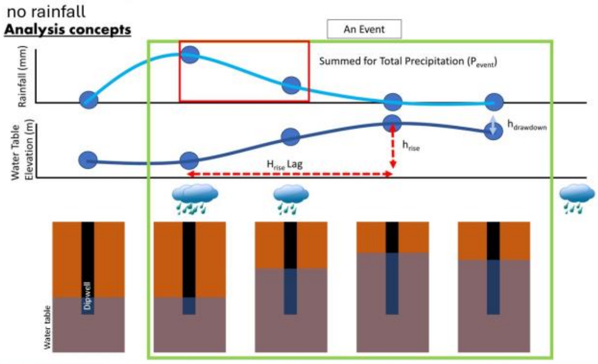
## Study sites




- In Ireland, 80,000 ha (of ~350,000 ha total) of permanent grassland on peat soils are targeted in the Climate Action Plan for reduced management intensity
- REWET sites are located on these historically drained grassland sites throughout the midlands of Ireland
- The main objective of REWET is to assess the hydrologic impact of actively managing the water table on these grassland peat sites by blocking surface drains. The project's specific aims are to:
  - Establish suitability of sites for rewetting
  - Identify and undermine artificial drainage features
  - Measure the impacts on the hydrology at the field scale and in the surrounding lands
  - Evaluate additional benefits of rewetting
- For the preliminary data analysis, two field sites were chosen for their geographic proximity, differing depths of peat soils, and available data

## Data analysis

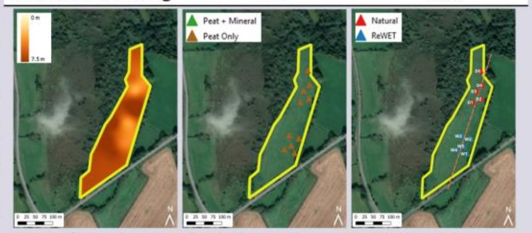
- Event-based analysis to determine water table rise, lag time, and drawdown following precipitation
- A new event begins when there is rainfall after a period of at least 12 hours of no rainfall



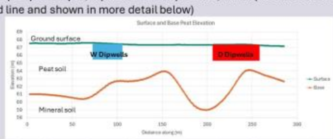

## Site A: Preliminary results

- Fen peat
- The surface drain at Site A was blocked on 28/03/2023
  - 'Natural' dipwells (D) are located downstream of the dam
  - 'ReWet' dipwells (W) are located upstream of the dam

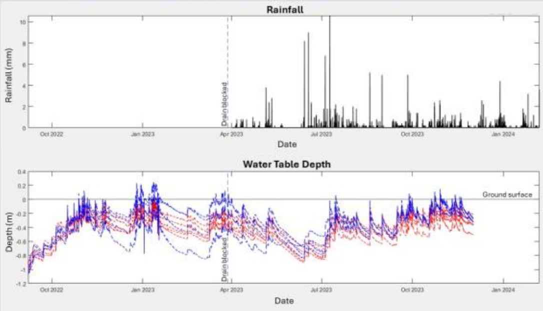
| | D dipwells ▲ mean WT depth (cm) | W dipwells ▲ mean WT depth (cm) |
|---|---|---|
| Pre-drain blocking | -40.5 | -35.6 |
| Post-drain blocking | -44.1 | -36.9 |



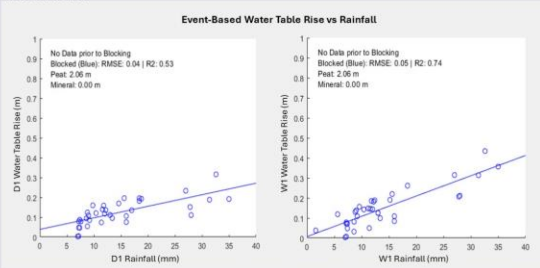

Above (L – R): Map of peat depth, dipwell soil composition, and dipwell location and site cross section (dashed line and shown in more detail below)



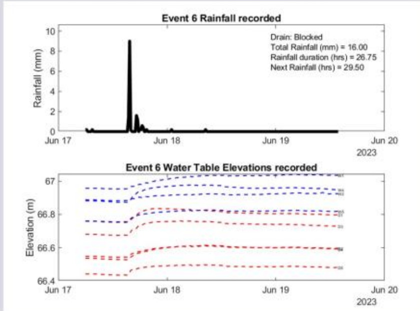

Above: Cross section of site surface and base peat elevations with average dipwell depths




Above: Rainfall and water table depth where the drain blocking is shown with a vertical dashed blue line and the ground surface on the water table depth figure is at 0 m (solid black line). The period used for the event-based analysis is April 2023 – December 2023 where there is overlapping precipitation and water table data




Above: Comparison of event-based water table rise and total rainfall at Site A in dipwells D1 and W1




Above: Example event output for a June 2023 event with 16 mm of rainfall over 26.75 hours

**Discussion:**

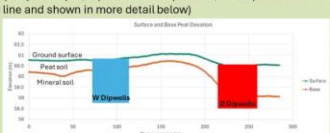
- All dipwells are located within peat soil at this site; they may all be measuring a perched water table rather than the regional water table
- No events were analysed pre-drain blocking due to the availability of local precipitation data
- The event-based water table rise showed a strong correlation to precipitation at this site
- The mean water table depth pre- and post-drain blocking showed little change, but the period measured means that we are comparing winter data (pre-) and summer data (post-), so more winter data post-blocking needs to be added

## Site B: Preliminary results

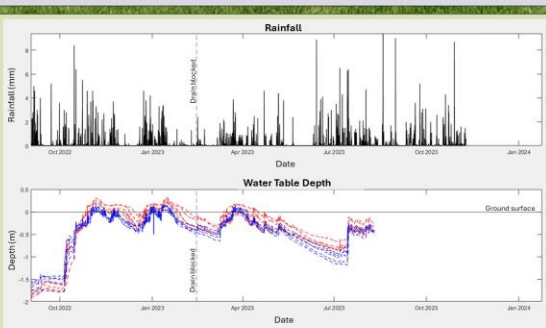
- Fen peat
- The surface drain at Site B was blocked on 14/02/2023
  - 'Natural' dipwells (D) are located downstream of the dam
  - 'ReWet' dipwells (W) are located upstream of the dam

| | D dipwells ▲ mean WT depth (cm) | W dipwells ▲ mean WT depth (cm) |
|---|---|---|
| Pre-drain blocking | -41.6 | -50.1 |
| Post-drain blocking | -38.2 | -49.4 |

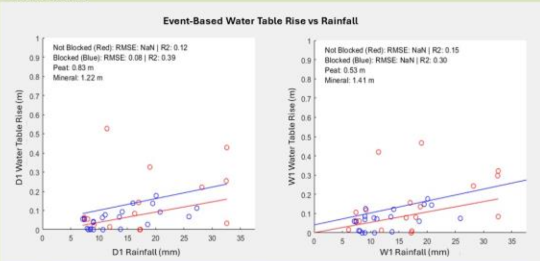

Above (L – R): Map of peat depth, dipwell soil composition, and dipwell location and site cross section (dashed line and shown in more detail below)



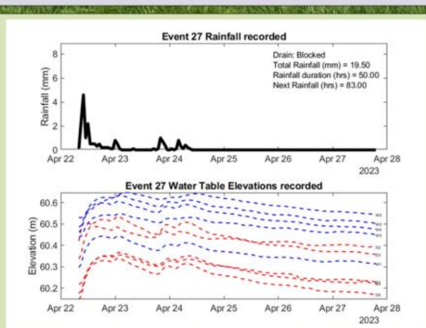

Above: Cross section of site surface and base peat elevations with average dipwell depths




Above: Rainfall and water table depth where the drain blocking is shown with a vertical dashed blue line and the ground surface on the water table depth figure is at 0 m (solid black line). The period used for the event-based analysis is September 2022 – August 2023 where there is overlapping precipitation and water table data




Above: Comparison of event-based water table rise and total rainfall at Site B in dipwells D1 and W1; red = not blocked, blue = blocked




Above: Example event output for an April 2023 event with 19.5 mm of rainfall over 50 hours

**Discussion:**

- All dipwells go through the peat soil into mineral soil at this site; they may be measuring the regional water table
- The event-based water table rise shows a weak correlation to precipitation at this site, however this was a slightly stronger correlation after the drain was blocked indicating that more rainfall may be retained at the site post-drain blocking
- The mean water table depth pre- and post-drain blocking showed little change, but the period measured means that we are comparing winter data (pre-) and summer data (post-), so more winter data post-blocking needs to be added

Acknowledgements: This work is funded by the Department of Agriculture, Food and the Marine through RSF Grant 2021R454:Rewet.

# DECADES-LONG SUBSIDENCE INDUCED BY GROUNDWATER DRAINAGE AT CLARA RAISED BOG, IRELAND, DETECTED FROM SATELLITE THROUGH L- AND C-BAND INSAR

***E.P. Holohan,*** *University College Dublin & iCRAG*

# Decades-long subsidence induced by groundwater drainage at Clara raised bog, Ireland, detected from satellite through L- and C-band InSAR

E. P. Holohan [1,2] , A. Hrysiewicz [1,2], S. Fiaschi [1], I. Lokmer[1,2], & S. Regan [2, 3],

[1] UCD School of Earth Sciences, University College Dublin; [2] SFI Centre for Research in Applied Geosciences (iCRAG) & [3] National Parks and Wildlife Service;

## (1) Clara Bog: Cutting and restoration

- Following establishment of drains and cutting of turf at its margins in the 1990s (**Figure 1**) , Clara bog has had a well-established history of subsidence.

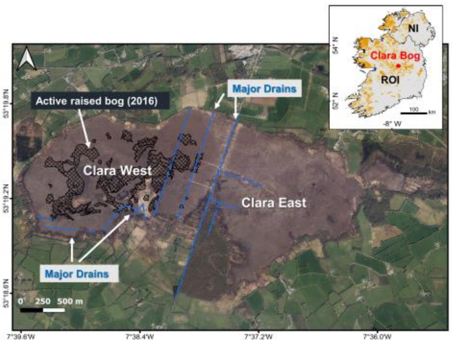



*Figure 1: Optical satellite image of Clara bog with major drains and area of active raised bog as surveyed in 2016 by NPWS.*

- Restoration works (e.g. drain blocking) undertaken on Clara West since the mid-2000s (with more planned) aim to stabilize the water table, the decline of which causes the subsidence.

## (2) Interferometry of Synthetic Aperture Radar (InSAR)

- Subsidence can potentially be mapped to mm-accuracy from space by using InSAR, a technique that compares the change in radar phase between two radar images (**Figure 2**).

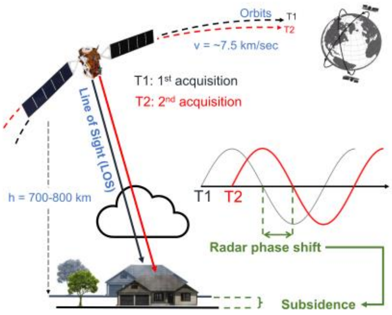



*Figure 2: Principle of InSAR. Note that the radar penetrates clouds, so regular imaging is possible in temperate (cloudy) Irish climate.*

- Clara bog thus provides an opportunity to test the effectiveness of InSAR for mapping and monitoring subsidence, and by extension the effectiveness of restoration.

## (3) Maps of Peat thickness and surface motion on Clara West

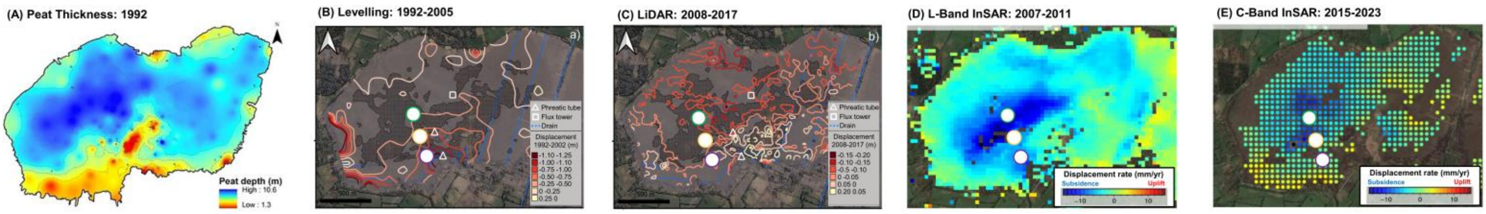
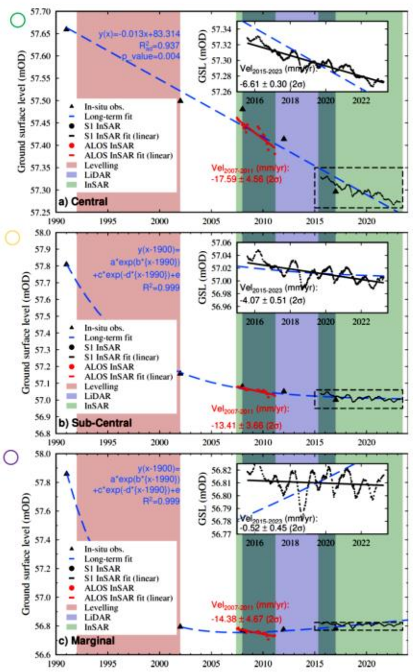



*Figure 3: In-situ and remote sensing data for Clara West. (A) Peat thickness map (Regan et al., 2019); (B) Contours of elevation changes between precise levelling surveys made in 1992 and 2005 (ten Heggeler et al., 2005); (C) Contours of elevation changes between precise levelling surveys made in 2008 and 2017 (Regan et al., 2019); (D) Surface motion rates in 2007-2011 from InSAR (SBAS) analysis of ALOS L-Band SAR data (this study); (E) Surface motion rates in 2015-2023 from InSAR (IPTA) analysis of Sentinel-1 C-Band SAR data (this study).*

- ***Levelling surveys*** revealed subsidence of up to 1.25 m (c. 10 cm/yr) in the south and west bog margins between 1992 and 2005 (**Figure 3**). ***LiDAR surveys*** indicated that this stopped by 2017, but that subsidence persisted in the bog center at a rate of about 1.3 cm/year.
- ***L-band and C-Band InSAR confirms*** the overall patterns seen in the LiDAR surveys (**Figure 3**). Marginal subsidence had reduced to c. 1.5 cm/yr by 2011 and ceased by 2019. Central subsidence has persisted in the bog center at a rate of about 1 – 1.5 cm/year.

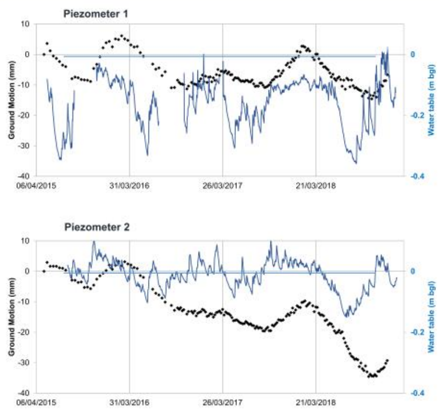
## (4) Time-series of peat surface motion on Clara West




- The InSAR data indicate a slight slowing of the central subsidence over time
- The marginal ground motion has ceased or even slightly reversed over time

*Figure 4: Synthesis of time series of > 30 years of ground motion data at Clara West from Levelling, LiDAR and InSAR. Note that the long-term curve fitting is done only for the LiDAR and Levelling data points.*

## (5) InSAR Ground Motion → Water Table Dynamics




- The InSAR time series data reveal annual bog surface oscillations, with highs in the winter and lows in the summers.
- These oscillations lag by a few weeks the rise and fall of water table levels at Clara West, as measured in 'floating' phreatic tubes (**Figure 5**).

*Figure 5: Time-series of water levels (blue) from phreatic tubes vs bog surface motion from InSAR (black) at the tube sites. See Figure 3B and C for phreatic tube locations.*

## (6) Conclusions

- Interferometry of SAR images (InSAR) from both L-band and C-band imagery successfully images historical and recent ground motions at Clara West.
- A long-term shift in subsidence locus from south to center is confirmed by InSAR .
- InSAR enables ground motion at raised bogs like Clara to be mapped to mm-precision. In principle, this could link to water table levels at these bogs, especially seasonal oscillations. Long terms surface motion rates seem to correlate with peat thickness.

This presentation has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 13/RC/2092_P2 and is co-funded by iCRAG partners.

An tSeirbhís Páirceanna Náisiúnta agus Fiadhúlra
National Parks and Wildlife Service

# SATELLITE C-BAND SAR BACKSCATTER INTENSITY CHARACTERISTICS OF IRISH PEATLANDS (CASE STUDY: ALL-SAINTS)

***Mahdi Kh. Azar,*** *University College Dublin & iCRAG*

# Satellite C-band SAR Backscatter Intensity Characteristics of Irish Peatlands (case study: All-Saints)

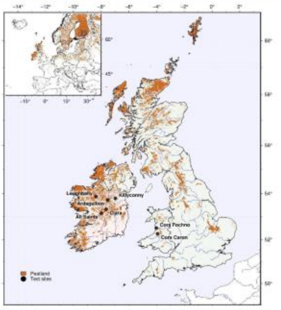

Mahdi Kh. Azar[1,2], Alexis Hrysiewicz[1,2], Shane Donohue[1,3], Shane Regan[4], Eoghan P. Holohan[1,2]


## 1. Problem Statement

**Peatlands** are a small natural carbon sink that over geological timescales sequester vast quantities of carbon. More than **80% of Irish bogs** are damaged, however, resulting in carbon emission, biodiversity loss, water quality issues and landslides.

Restoration of damaged bogs → Protecting peatlands

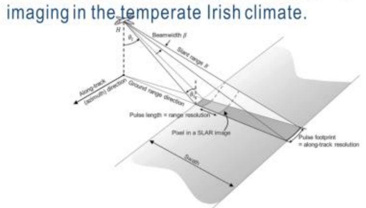
**Problem:** Monitoring at large scales (regional, national, or global)



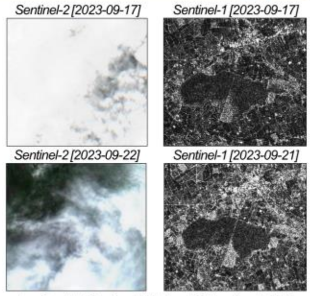

Distribution of Ireland and Britain peatlands

## 2. Synthetic-Aperture Radar Remote Sensing

**Synthetic-Aperture Radar (SAR)** imaging is an active remote sensing approach **that can penetrate clouds**, thus overcoming limitations of optical imaging in the temperate Irish climate.

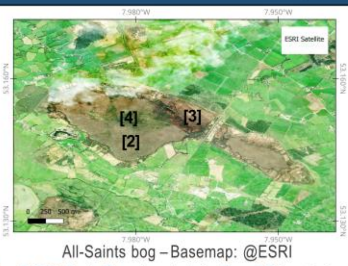



Acquisition geometry of SAR sensor




Examples of optic (Sentinel-2 Natural Colour) and SAR (Sentinel-1 intensity) images over Clara Bog in same dates

## 3. Study Area




All-Saints bog – Basemap: @ESRI

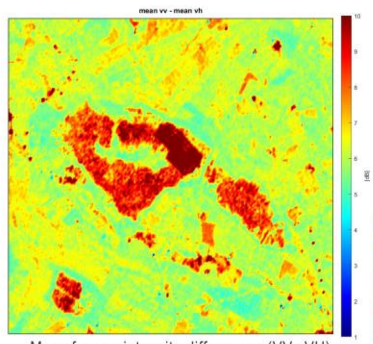

Map of restoration – Basemap: @ESRI

The **All Saints Bog**, located in Co. Offaly, Ireland, is a raised bog. **Restoration** efforts have been underway since around 2020 to rehabilitate/restore the **degraded** areas.

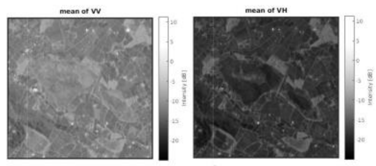
**Qualifying Interests based on NPWS:**

[1] Semi-natural dry grasslands; [2] Active raised bog; [3] Degraded raised bogs still capable of natural regeneration; [4] Bog woodland.

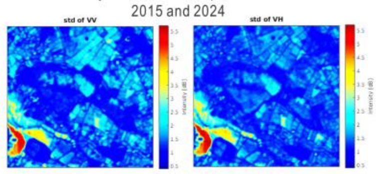
## 4. Spatial Analysis of SAR Backscatter Intensity




Map of mean-intensity differences (VV – VH)



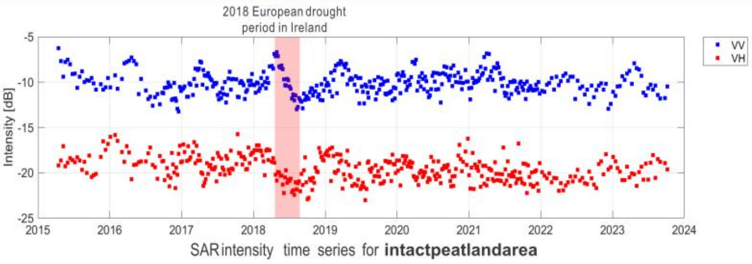

Mean intensity from VV and VH polarisation between 2015 and 2024



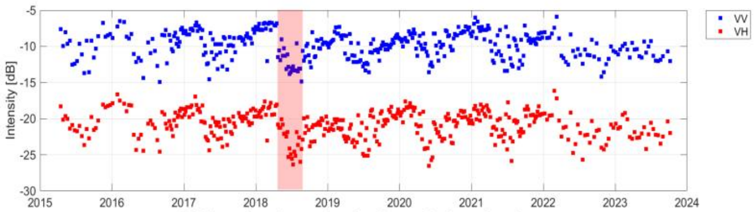

Standard deviation intensity from VV and VH polarisation between 2015 and 2024

1. Mean of VV is higher than mean of VH;
2. STD is higher on the degraded areas compared to other areas;
3. The difference (VV - VH) is higher on: (1) degraded parts (> 10 dB); (2) intact parts (8-9 dB); and (3) wooden parts (5-6 dB).

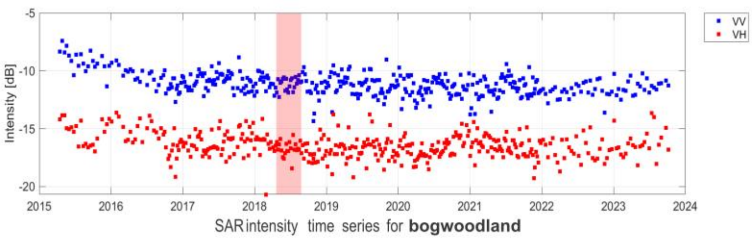
## 5. Temporal Analysis of SAR Backscatter Intensity




SAR intensity time series for **intact peatland area**



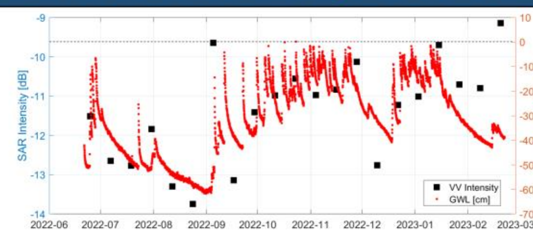

SAR intensity time series for **degraded peatland area**



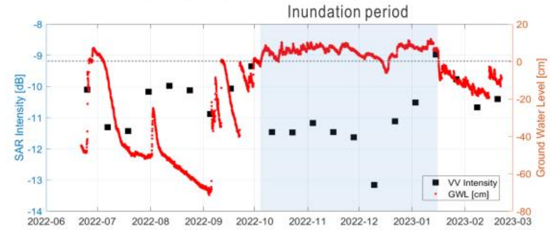

SAR intensity time series for **bog woodland**

1. Annual oscillations are linked to wet and dry periods.
2. Larger drop (~5 dB) in the intensity occurred for dry summer during the 2018 dry summer.
3. No annual oscillations of intensity are observed over wooden areas.

## 6. Relationship between SAR Intensity and Groundwater Levels




SAR intensity (black) vs. groundwater levels (red) for AS29 location




SAR intensity (black) vs. groundwater levels (red) for AS1 location

1. Strong relationship between SAR backscatter intensity and in-situ groundwater levels.
2. SAR intensity can monitor the rewetting stage: decrease in SAR intensity due to the inundation (2-4 dB) over a short period.

## 7. Conclusions

- **Variations in SAR backscatter intensity of differing polarisations can be used to map accurately different ecological conditions on All Saints raised bog, Ireland.**
- **Bog woodland, intact bog and cutover peat (degraded area) are distinguishable regarding their temporal behavior in VV and VH polarization intensity values**
- **Groundwater level at All Saints is positively correlated with Intensity of backscattering (unless flooded).**


This presentation has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) under Grant Number 13/RC/2092_P2 and is co-funded by iCRAG industry partners.



1 SFI Research Centre in Applied Geosciences (iCRAG), University College Dublin, Dublin, Ireland
2 UCD School of Earth Sciences, University College Dublin, Dublin, Ireland
3 UCD School of Civil Engineering, University College Dublin, Dublin, Ireland
4 National Parks and Wildlife Service, Ireland

## LINKS BETWEEN SATELLITE INSAR, GROUND SURFACE MOTION AND WATER TABLE FLUCTUATION AT TEMPERATE RAISED PEATLANDS

***Alexis Hrysiewicz,*** *University College Dublin & iCRAG*

# Links between satellite InSAR, ground surface motion and water table fluctuation at temperate raised peatlands

**Alexis Hrysiewicz**[1,2], Eoghan P. Holohan[1,2], Shane Donohue[1,3], Chris D. Evans[4], Jennifer Williamson[4], A. Jonay Jovani-Sancho[4,5], Nathan Callaghan[4], Jake White[6], Justin Lyons[6], Joanna Kowalska[6] and Hugh Cushnan[8]

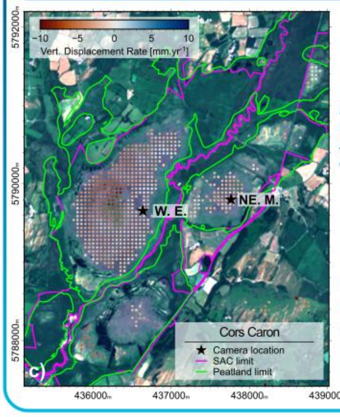
## 1) Radar remote sensing for temperate raised bogs

**In the context of global warming, it is crucial to estimate Greenhouse Gas (GHG) emissions from peatlands. Peatland preservation is key to achieving national and emissions targets.**

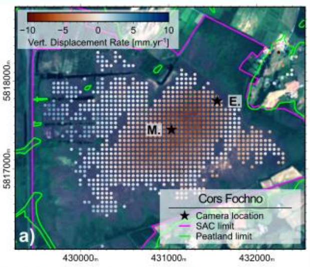


- **Greenhouse Gas emissions are linked to groundwater levels and ground surface levels** in peatland areas.
- **Remote sensing observations** from satellites can help for large-scale peatland monitoring.
- **Optical satellites** have problems with cloud cover (i.e., over Ireland).
- Because radar satellites can penetrate clouds, **peat surface displacements - estimated from radar satellites and InSAR method -** could be **an efficient proxy of peatland groundwater levels**, but we need **a robust ground validation**.

## 2) Mapping of peat motion rate from InSAR



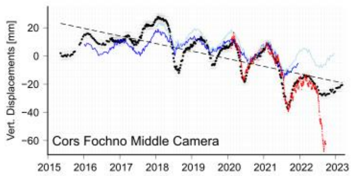

*Examples of velocity maps of InSAR-derived vertical displacements.*

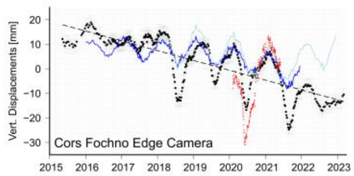


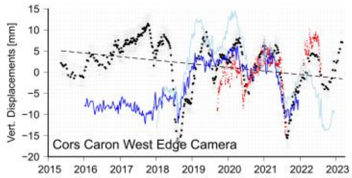

**Cors Fochno** (Wales, United Kingdom):
**(1) subsidence in the centre**
**(2) uplift at the edges.**

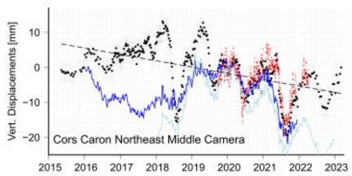
**Cors Caron** (Wales, United Kingdom):
**(1) overall subsidence.**

## 3) Ground validation of InSAR-derived peat surface motions



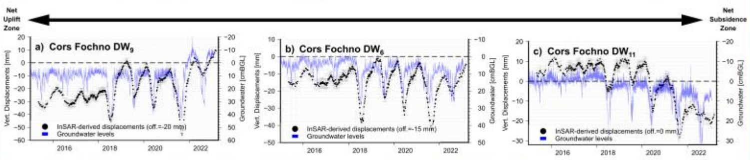




*Time series of InSAR **"combined"** (in black) and **in-situ** (in red) vertical displacements from Peat cameras. The InSAR-derived results are represented by black dots and in-situ with red dots. Blue (2015-2021 release) and light blue (2018-2022) corresponds to InSAR-derived displacements from European Ground Motion Service.*

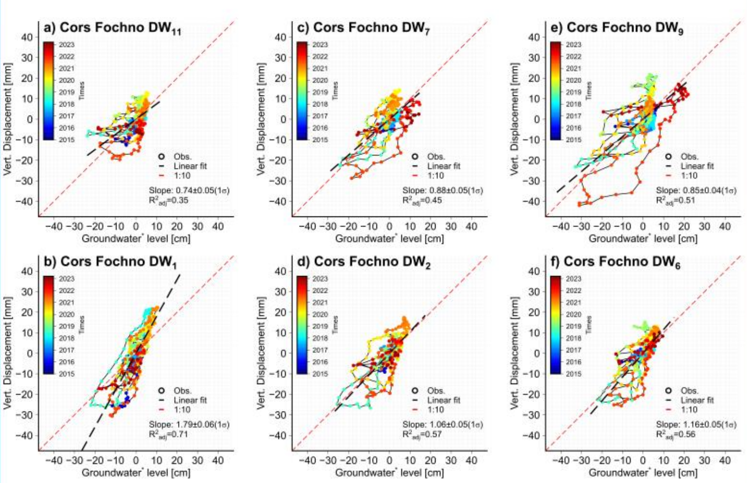
- **Novel in-situ method (peat cameras)** to measure the peat surface displacements (peat cameras) on two Welsh raised peatlands (Cors Fochno and Cors Caron).
- **Modified InSAR approach** to minimise the underestimation of annual peat surface oscillations, by combining long-term and short-term temporal-baseline networks.
- **High similarity** between InSAR and in-situ results: **Pearson's correlation coefficient > 0.8**.

## 4) Proxy of peatland groundwater level changes




*Peat surface displacement and groundwater level time series on Cors Fochno (Wales, UK)*

- The **peat surface displacements** (i.e., annual oscillations) are synchronous with or lag slightly behind **groundwater level changes**.

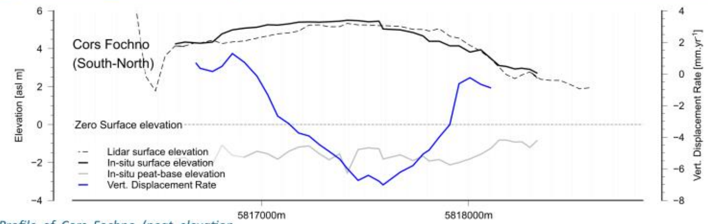



*Corrrelation between peat surface displacements and groundwater levels on Cors Fochno (Wales, UK)*

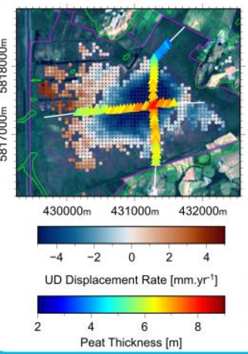
- **Ratio of 1:20 to 1:10** between short-term peat surface displacement and groundwater level.

*(for raised bogs)*

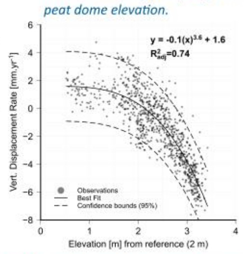
## 5) Linkages with peat thickness and motions



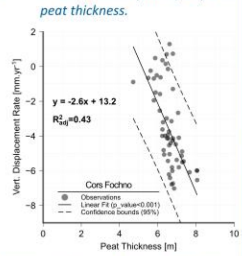

*Profile of Cors Fochno (peat elevation, peat thickness, peat surface motions).*




*Peat surface displacement rates on Cors Fochno (Wales, UK) with peat dome elevation.*



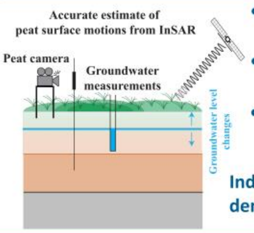

*Peat surface displacement rates on Cors Fochno (Wales, UK) with peat thickness.*




**Relationships between** long-term peat surface displacement **rates,** peat dome **elevation and peat thickness.**

*(for raised bogs)*

## 6) Conclusions over temperate raised bogs




- **Peat surface motions** can be estimated from InSAR remote sensing.
- **Long-term** peat surface displacements **can be a spatial indicator of peat thicknesses (or locations).**
- **Short-term** peat surface displacements **are an indicator of variations** in groundwater levels (**ratio of 1:20 to 1:10**).

**Indirect observations of groundwater levels with unprecedented spatial/temporal resolution.**

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**References:**

Hrysiewicz, A., et al. (2023). "Estimation and Validation of InSAR-derived Surface Displacements at Temperate Raised Peatlands" Submitted to Remote Sensing of Environment.
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8 RPS Group, Northern Ireland, United Kingdom

# LARGE SCALE CLIMATIC TELECONNECTION FOR PREDICTING EXTREME HYDRO-CLIMATIC EVENTS IN SOUTHERN POLAND

***Dominika Dąbrowska***, *University of Silesia in Katowice, Poland*

# Largescaleclimatic teleconnection for predicting extreme hydro-climatic events in southern Poland

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## ABSTRACT

Extreme weather events such as heavy rainfall occasionally causeflooding and have severe socio-economic impacts. For example, in southern Poland, an extreme rainfall event occurred and seriously impacted country in 1997, 2001 and 2010. Oceanic-atmospheric teleconnection patterns (OATPs) could affect hydro-climatic events over large distances across the world including southern Poland. Therefore, various climatic and oceanic parameters such as North Atlantic Oscillation (NAO) and Sea Surface Temperatures (SSTs) of surrounding seascould be employed asinputs to predict extreme hydro-climatic events. Hydro-climatological processes are generally associated with high uncertainty, and it is believed that class prediction is much reliable than the predictions via regression basedpoint prediction modeling tools. In this regard, this research will focus on developing a hybrid data driven-based modeling framework to predict extreme weather events in southern Poland up to 6-month lead time. The hybridization of two data mining techniques of decision tree and association rules is proposed to extract affiliation between Pszczyna synoptic station as target and stationary OATPs/SSTs time series as inputs. Two major steps of the proposed model are

i) Classification of the input data and selecting the most effective classes and extracting patterns involved in the data. ii) Application of the decision tree method which can identify the dominant traits for the classification of the most effective groups and performance of association rules to extract the involved information within the data. To examine the accuracy of the rules and class predictions, confidence and Heidke Skill Score (HSS) measuresare calculated and comparedfor different input combinations.

The contributions and innovations of this researchare summarized as:

1.By evaluating the datareliability, this researchwill investigate the useof oceanic-atmosphericsignals aspredictors to predict hydro-climatic extreme events.

2.This research proposes the association mining tool to extract (explain) the teleconnection pattern between hydro-climatic parametersand the construction of if-then rules.

## INTRODUCTION

Extreme hydro-climatic events carry significant weight not only due to their occasional aftermaths, such as the socio-economic impacts stemming from floods, droughts, and typhoons but also due to their substantial contributions to freshwater resources. In Poland, floods, primarily resulting from heavy or prolonged precipitation, standout as a prominent category of natural disasters.

The average annual amount of precipitation in Poland for the same period was 630 mm. The analysis of the data shows that over 60% of the country has annual rainfall that is lower than the areaaverage.The lowest rainfall falls in February and the highest rainfall occurs in July. In February, approximately 30 mm of precipitation falls, while in July it is three times as much. The spatial distribution of rainfall in Poland indicates that a large share of rainfall in the south of the country is due to the presence of mountains. In the north, the least amount of rainfall is observed,which does not reach 600 mm per year. Uplands (southern Poland) and lake districts are characterized by an increase in the annual precipitation (up to 700–750 mm). Reduced precipitation relative to altitude can be observed on leeward slopes or in the area of isolated hills.

In Poland, extreme precipitation can also be observed in the form of wide-spreadprecipitation or heavy convective precipitation. The first of them cover a large area of the country, but are not very intense. They are characteristic of the summer months and may cause negative hydrological effects. Poland has been subject to extreme floods many times. In the 20th century, the largest floods occurred in 1934, 1947, 1979 and 1997. The last of them is called the flood of the millennium. This flood covered the upper catchments of the Oder, Morawa and Vistula. Some areas received almost 600 mm of rainfall in a few days.

## METHODOLOGY

The frequency and intensity of such extreme events are closely tied to oceanic-atmospheric teleconnection patterns (OATP), playing a pivotal role in modulating regional climate variability. These patterns encompassatmospheric circulation patterns that link Sea Surface Temperature (SST) anomalies with circulation patterns, thereby connecting distant climate fluctuations.

The frequency and intensity of such extreme events are closely tied to Examples of OATP include the North Atlantic Oscillation (NAO), Southern Oscillation Index (SOI), Scandinavian pattern (SCAND), Polar, and El Niño Southern Oscillation (ENSO). Establishing a teleconnection between weather events and OATP, combined with local-scale factors such as SST of near seas, could enhance the prediction of extreme weather events and mitigate their socioeconomic impact. Numerous studies globally have examined the relationship between OATP and hydro-climatic parameters. Similarly, in Poland, teleconnection patterns significantly influence hydro-climatologic systems,impacting extreme precipitation events and precipitation patterns.

For this study, OATP signals and local parameters were utilized to predict extreme weather events in Pszczyna, a town situated in southern Poland, where the climatic influence of air masses from the Atlantic prevails. Data preprocessing involved sensitivity analysis to select effective parameters, trend and seasonality analysis, and standardization procedures like Z-Score standardization. Subsequently, data were categorized into different classes based on their mean (μ) and standard deviation (σ) values. Conventional methods like linear or nonlinear regression may struggle to unveil potential teleconnections between hydro-climatic parameters due to the complexity and uncertainties associated with long-distance teleconnection processes.Therefore, data mining tools offer a promising alternative, enabling the extraction of hidden predictive information from large databases. Data mining methods, including association rules, can reveal dominant patterns among large datasets and establish cause-and-effect relationships between multiple hydro-climatic variable sets. Thus, as part of the second step, association rules will be applied to recognize dominant patterns among large datasets for extracting rules. It's worth mentioning that properly-classified data in the preprocessing could lead to the appropriate set of rules. According to the association rule, D→E, whenever D occurs as an antecedent, and E occurs as a consequence. To determine whether such a rule is accurate, support (SUPP) and confidence (CONF) criteria could be used. In this instance, SUPP indicates the percentage of D and E occurrences simultaneously compared to the total number of occurrences (Equation 1). In Equation 2, the CONF criterion calculates the fraction of simultaneous D and E occurrences.

$$SUPP\,(D \rightarrow E) = P(D \cup E) \tag{1}$$

$$CONF\,(D \rightarrow E) = P(D \mid E) = \frac{\mathrm{SUPP}\,(D \cup E)}{\mathrm{SUPP}\,(D)} \tag{2}$$

## RESULTS

In this study, association rules were applied to recognize dominant patterns among large datasets, considering parameters such as SUPP and CONF criteria to assessthe accuracy of the rules. After detrending the data, monthly SSTs and OATP signals were classified into five classes(very high, high, medium, low, and very low) within bounds of μ±iσ (where i= ±0.5,±1) as presentedin Fig 1. The association rule mining process yielded more than 10000 patterns with confidence over 0.5. For Examples:

North Sea SST=M, MEDITERANIAN Sea SST=M, NAO=VL, Nino region 3.4=M (7 times)-> precipitation=High (7 times) conf: (1).

Baltic sea SST=VH, MEDITERANIAN Sea SST =H, Nino region 3.4=M (9 times) -> precipitation=High (9 times) conf: (1).

North Sea SST =VH, Nino region 3.4=M (55 times) -> precipitation=High (28 times) conf: (51)

The results indicated that SCAND and Polar signals were among the least influential OATPs affecting extreme weather events in the studied area.

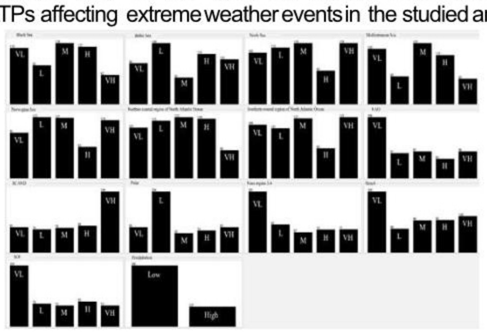


Fig. 1. Classified data

## HYDROMORPHOLOGY OF RIVER CHANNELS AND FLOODPLAINS: NATURE-BASED SOLUTIONS

***Peter Glanville**, SLR Consulting Ireland*

SLR

# Hydromorphology of River Channels and Floodplains: Nature-Based Solutions

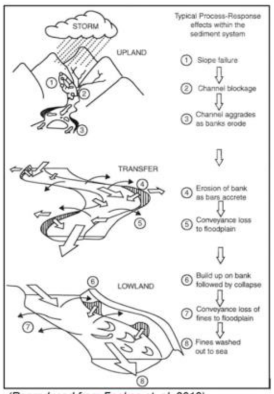
IAH Conference – 16th and 17th April 2024

## River Hydromorphology

- How have we managed our rivers?
- What do our rivers look like?
- What do we want from our rivers and what will it take?

## Role of Sediments

Fluvial Geomorphology: The role of sediment in catchment processes




(Reproduced from Fookes et. al. 2012)

**Fig 1.** Fluvial Geomorphology: The Role of Sediment in Catchments

**Fig 4.** Modified Channel (Drainage District Scheme)

## Hydromorphology of Stradbally River

The geomorphology attributes scored are:

- Channel form and flow type;
- Channel vegetation types;
- Substrate bedload condition;
- Barriers to continuity;
- Bank structure and stability (Left Bank & Right Bank);
- Bank vegetation (Left Bank & Right Bank);
- Riparian land cover (Left Bank & Right Bank); and
- Floodplain connectivity (Left Bank & Right Bank).


## Author

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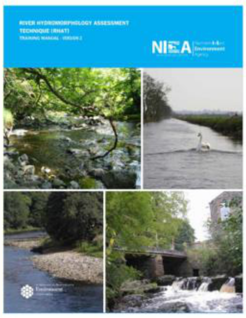
**Fig 2.** Rivers


**Fig 3.** Stradbally River, Co. Laois: Channel designations

Stradbally River - Modified Channel

Stradbally River - Natural Channel




WFD Hydromorphology Score Class:

> 0.8 = High

> 0.6 – 0.8 = Good

> 0.4 – 0.6 = Moderate

> 0.2 – 0.4 = Poor

< 0.2 = Bad

**Stradbally River Hydromorphology Score = Bad**

## Key Irish River Species: Hydromorphology Indicators?


## Floodplain Restoration

European Environment Agency

*EEA Report No 24/2019*

- Floodplains are part of Europe's natural capital
- Covering 7 % of the continent's area and up to 30 % of its terrestrial Natura 2000 site area.
- 70-90 % of floodplains have been environmentally degraded.
- Natural and restored floodplains provide an alternative to structural measures for providing flood protection
- Support achieving higher quality ecosystem service like improved water quality, improved conditions for biodiversity conservation and improved recreational value.

## Reversing Biodiversity Loss, Climate Resilience, Water Quality


A European Green Deal

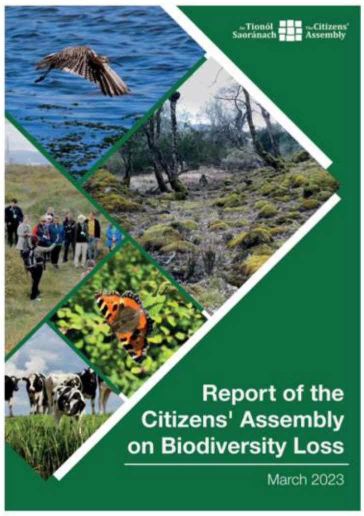
Striving to be the first climate-neutral continent

EU Biodiversity Strategy 2030

## Reversing Biodiversity loss in Ireland – Rivers

Report made 159 recommendations. Fourteen recommendations relating specifically to freshwater (rivers and lakes) with five key recommendations:

- **Recommendation#92:** Single body to oversee and co-ordinate, manage, implement, and enforce legislation and policies relevant to freshwater.
- **Recommendation#95:** Riparian buffer zones must be expanded.
- **Recommendation#100:** The 1945 Arterial Drainage Act is no longer fit for purpose.
- **Recommendation#101:** Nature-based solutions and should include whole of catchment area hydromorphology planning and restoration.
- **Recommendation#102:** Develop a National Hydromorphology Plan.



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Coran Kelly

David Ball

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