Groundwater & Geotechnics

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS - Irish Group

Proceedings of the 45th Annual Groundwater Conference

Tullamore Court Hotel, 15th & 16th April 2025

INTERNATIONAL ASSOCIATION OF
HYDROGEOLOGISTS
(IRISH GROUP)

Presents

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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).

For more information please refer to:	www.iah-ireland.org
Future events:	www.iah-ireland.org/upcoming-events/
IAH Membership (new or renewal):	www.iah.org/join_iah.asp
	www.iah.org/payonline

2025 IAH (Irish Group) Conference **Groundwater & Geotechnics**

It is my great pleasure to welcome you to this year's annual conference of the International Association of Hydrogeologists (Irish Group). As Conference Secretary, I am delighted to introduce this year's theme: Groundwater and Geotechnics – a subject of growing importance in Ireland and beyond.

The intersection of groundwater and geotechnical engineering is critical in addressing many of today's pressing environmental and infrastructural challenges. Whether we are designing foundations for large infrastructure projects, managing groundwater during tunnelling and excavation, or ensuring slope stability in an increasingly unpredictable climate, the integration of hydrogeological and geotechnical expertise is essential. This year's conference brings together leading experts, practitioners, researchers, and policymakers to explore the synergies between these disciplines and foster a deeper understanding of the complex interactions between groundwater and the built environment.

Over the course of the conference, we will engage with a diverse range of technical presentations, case studies, and discussions. Our themed sessions will cover aspects such as the role of groundwater in geotechnical stability, advances in site investigation techniques, the challenges posed by groundwater control in construction, and the latest innovations in numerical modelling and risk assessment. These sessions will provide invaluable insights into best practices and emerging trends that are shaping the future of groundwater and geotechnical engineering.

The Irish hydrogeological community has long been at the forefront of research and applied practice in groundwater management. The challenges we face – ranging from climate change impacts to sustainable water supply management – underscore the importance of collaboration between hydrogeologists and geotechnical engineers. By working together, we can develop more resilient infrastructure, protect vital groundwater resources, and contribute to sustainable land development practices.

This conference would not be possible without the dedication of our organizing committee, our generous sponsors, and the authors and presenters who have contributed their expertise to this event. I would like to extend my sincere gratitude to everyone involved in making this conference a success.

I encourage you to take full advantage of the networking opportunities, participate actively in discussions, and engage with your peers to exchange knowledge and ideas. Together, we can continue to advance our understanding of the vital relationship between groundwater and geotechnics and drive innovation in both fields.

On behalf of the International Association of Hydrogeologists (Irish Group), I welcome you to what promises to be an engaging and insightful conference.

Enjoy the conference and thank you for your participation!

Gerry Baker
IAH (Irish Group)
Conference Secretary

2025 IAH (Irish Group) Committee:

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

Cover Photo Credit: Gerry Baker, Arup - Dewatering excavation to expose pile caps in gravel aquifer, Co. Cork.

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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 & Geotechnics

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co Offaly
Tuesday 15th April – Wednesday 16th April 2025

Programme Day 1: Tuesday 15th April

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

INTRODUCTION

09:30 – 09:45 Welcome: Ray Flynn (*President IAH Irish Group*)

SESSION I

09:45 – 10:20 **KEYNOTE 1**: Martin Preene (Coffey Geotechnics) *Groundwater Control for Large Infrastructure Projects*

10:20 – 10:50 Eric Farrell (AGL (Retired)): *Developing Practical Engineering Solutions to Dewatering Challenges*

10:50 – 11:05 *Q&A*

11:05 – 11:35 *Tea & Coffee*

SESSION II

11:35 – 12:00 Mike Long (UCD): *Case Histories: Subsidence induced by ground water pumping & lowering*

12:05 – 12:25 James Watson (OGI) *Early-stage identification, assessment, and mitigation of Groundwater and Geotechnical Risks during Construction*

12:25 – 12:45 Carl Gilbert (Tetra-tech): *Assessing Groundwater Risks from Large Stormwater Storage Tanks: A Conceptual Site Model Approach*

12:45 – 13:00 *Q&A*

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

SESSION III

14:00 – 14:40 **KEYNOTE 2**: Stephen Thomas (OGI) *Groundwater Engineering for Hydrogeologists and Geotechnologists*

14:40 – 15:00 Matt Craig (EPA): *Implementing the new Abstraction Licensing Regime*

15:00 – 15:20 Peter Murphy (Tetra-tech): *Landslide Geotechnical Remedial Design informed by multi-disciplinary investigation*

15:20 – 15:35 *Q&A*

15:35 – 16:05 *Tea & Coffee*

SESSION IV

16:05 – 16:25 Alison Orr (Arup): *Hydrogeological Assessments to develop Groundwater Flood Relief Measures.*

16:25 – 16:45 Mohamad Soboh (UCC): *Modelling and Monitoring the Groundwater Flood risk in Cork City*

16:45 – 17:05 Ted McCormack (GSI): *Groundwater Flooding at Lough Funshinagh, Co. Roscommon: Addressing the Knowledge Gaps*

17:05 – 17:20 *Q&A*

17:20 *Posters & Wine Reception*

19:00 *Social event sponsored by IAH – Irish Group*

Programme Day 2: Wednesday 16th April

08:30 – 09:30	Conference Registration: tea, coffee & exhibits
SESSION V	
09:30 – 09:55	Farimah Fattahi Masrour (UCG): *Embankments over blanket peat in Co Donegal: interpretation of piezometer data*
09:55 – 10:15	Saeed Azadnejad (iCrag): *Use of Satellite Data (InSAR) to identify rail infrastructure subsidence on peat*
10:15 – 10:30	Early Career Winner: Sajjad Ahmad (TCD): *Hydro-geotechnical properties of peat bunds used in the restoration of raised bogs*
10:30 – 10:35	Early Career Runner Up: Shuoshuo Xu (UCD): *Design Optimization of Large-Scale Shallow Geothermal Systems for District Heating at UCD*
10:35 – 10:40	Early Career Runner Up: Oisin Leonard (UCG): *Remote Activation of Salt Tracer Injection to Enhance Discharge Measurements in a Peatland Catchment*
10:35 – 10:50	*Q&A*
10:50 – 11:20	*Tea & Coffee*
SESSION VI	
11:20 – 11:45	Ken Scally (Normec): *Decoding Coal Tar's Hidden Clues: Forensic Analysis of PAHs and Alkylated Homologs for Smarter Waste Identification at Contaminated Land Sites*
11:45 – 12:10	Mirsina Aghdam (WSP): *Natural Radionuclides as Tracers of River-Aquifer Interactions: A Novel Approach for Monitoring Surface Water Dynamics in Irish River Systems*
12:10 – 12:30	Paul Walker (Socotec): *Emerging Contaminants: Microplastics, the current state of knowledge*
12:30 – 12:45	*Q&A*
12:45 – 13:00	*Conference Closing Address: Gerry Baker (Conference Secretary – IAH Group)*
13:00	*Buffet lunch in Tullamore Court Hotel*

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SESSION I

GROUNDWATER CONTROL FOR LARGE INFRASTRUCTURE PROJECTS

Martin Preene, *Coffey Geotechnics Limited, Harrogate, UK*

ABSTRACT

Groundwater control is often a key part of temporary works for construction projects of all scales. However, large infrastructure schemes such as linear projects (pipelines, road, rail and metro schemes) and deep excavations (such as wastewater schemes, power supply and distribution projects) present particular challenges, which can include: very large lateral extent of the works (which may interact with different ground conditions, multiple aquifers and diverse geological zones); significant depth of excavations; the presence of nearby sensitive structures or water-dependent features which may be affected by the drawdown effects of groundwater lowering; and the potential for increased regulatory scrutiny. This paper discusses possible groundwater control strategies for infrastructure projects, including the importance of good conceptual models and the risks of external impacts. Key points are highlighted by reference to case histories.

Key words: *Infrastructure, dewatering, groundwater control, conceptual models*

THE CHALLENGES OF LARGE INFRASTRUCTURE PROJECTS

Many large infrastructure projects involve excavations that extend below groundwater level, and will require temporary works engineering measures to control groundwater. There is no simple definition of what constitutes a ‘large infrastructure’ project but examples include linear infrastructure projects (such as pipelines, road, rail and metro schemes) and excavations that involve large or deep excavations, such as are often required for wastewater schemes, power supply and distribution projects, and in the development of mining sites.

Such large projects present challenges, which can include: very large lateral extent of the works (which may interact with different ground conditions, multiple aquifers and diverse geological zones); significant depth of excavations; the presence of nearby sensitive structures or water-dependent features which may be affected by the drawdown effects of groundwater lowering; and the potential for increased regulatory scrutiny.

This paper will discuss possible groundwater control strategies for infrastructure projects, including the importance of good conceptual models and the risks of external impacts. Key points will be highlighted by reference to case histories.

POSSIBLE GROUNDWATER CONTROL STRATEGIES

A wide range of groundwater control methods are available for application in various geometries and various geological settings in both soil and rock. Further details of methods can be found in CIRIA Report C750 (Preene *et al.*, 2016) and Cashman and Preene (2021).

On infrastructure projects groundwater control is typically applied in one of three strategies:

1. Groundwater control strategies dominated by pumping. This approach uses the collective effect of pumping from arrays of wells or sumps to lower groundwater levels below the proposed excavation (Figure 1a). With this strategy there is a requirement for continuous pumping of groundwater, often at high flow rates if highly permeable strata are present. The open pumping approach, most commonly applied by sump pumping, allows groundwater to enter the excavation or tunnel, from where it is

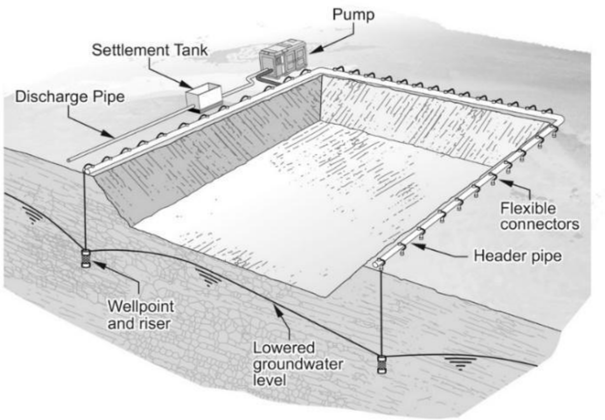
pumped away. Pre-drainage methods, which include wellpoints, deep wells and ejector wells, are applied by pumping from an array of wells to lower groundwater levels in advance of excavation.

2. Groundwater control strategies dominated by exclusion. This strategy uses physical cut-off walls (such as steel sheet piles or concrete secant pile walls) or zones of low permeability ground treatment (such as grouting or ground freezing) to exclude groundwater (Figure 1b). The barriers may be designed to form a seal into any low permeability strata below the excavation. The water trapped within the area enclosed by the low permeability barriers must be pumped away, but otherwise the required rates of continuous pumping are much lower than for pumping dominated strategies. This can be a useful characteristic where there is concern about external impacts, or if the environmental regulatory regime requires that rates of groundwater abstraction be minimised.
3. Groundwater control by fluid counter pressures. This strategy can be used on tunnelling and shaft sinking projects (Figure 1c). The relatively confined geometry of the exposed soil or rock in these cases can allow the use of methods that pressurise the tunnel face or shaft bottom with a fluid such as compressed air, water or bentonite slurry. This excludes groundwater by applying a fluid counter pressure, approximately equal to groundwater pressure. This type of method includes compressed air tunnelling and closed face TBMs of the earth pressure balance (EPB) type and slurry type (Shirlaw, 2012; Warren et al., 2018), and also as the flooded caisson method of shaft sinking (Allenby and Kilburn, 2015; Smith, 2018).

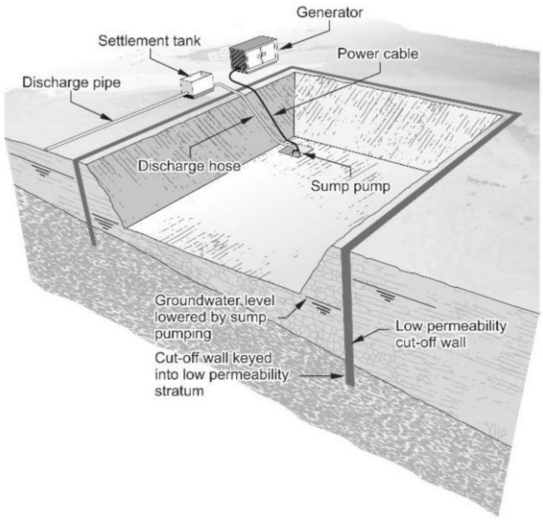
For all strategies the principal method (pumping, exclusion or fluid counter pressures) may be used in combination with secondary methods from other strategies. Furthermore, on large schemes there may be different strategies used in different sections or for different types of structure. For example, a linear transportation project may use fluid counter pressure methods for tunnel construction, and apply other methods, based on pumping and/or exclusion, for other elements such as cross passages or station structures (see Case History 1). Artificial recharge may be used as part of efforts to minimise any lowering of groundwater levels caused by pumping (Case History 1).

A further option can be considered for tunnel projects where the geology and hydrogeology of the tunnel route have been thoroughly characterised. In this scenario, it may be possible to design the tunnel vertical alignment to target strata or beds that are more favourable to tunnelling. From a groundwater control perspective, that could involve identifying layers that are of lower permeability – such as more clayey soils or less fractured beds of rock – where groundwater inflows and associated risk of instability will be lower. On some projects, it may not be possible to vary the vertical alignment in this way; however, this approach has been used as a cost-saving and risk-reduction measure on many tunnels (see Case History 2). In London it is generally accepted that geological conditions affected the development of the deep level tunnel network of the London Underground (known as 'the Tube') from the 1860s to the 1960s (Paul, 2009). Most of the older deep level Tube tunnels were constructed in the low permeability very silty clays of the London Clay Formation, and there was relatively little tunnelling south of the River Thames, where unpredictable sand layers within the clays of the Lambeth Group made tunnelling difficult. Paul (2009) also suggests that a key reason why the development of the Berlin U-Bhan did not start until the late 1890s was the presence of high groundwater levels in the gravel aquifer below that city; work had to wait until the available groundwater control technologies were sufficiently advanced.

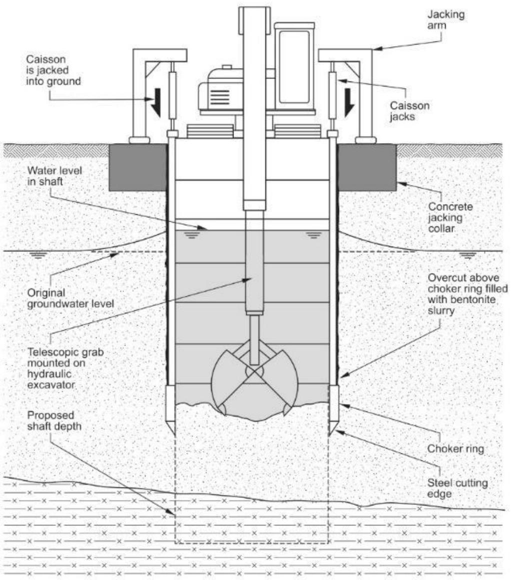
The groundwater control strategy chosen on a given project can have significant impacts on other aspects of the project, including wider temporary works measures and regulatory requirements. On large infrastructure projects it is essential to define an appropriate groundwater control strategy at as early a project stage as is practicable.



a) Groundwater control by perimeter wells (a form of 'pre-drainage'); wellpoint system shown



b) Groundwater exclusion using vertical cut-off walls; base of cut-off wall penetrates into low permeability stratum



c) Shaft construction by the wet caisson method

Figure 1: *Commonly used groundwater control strategies* (from Cashman & Preene (2021), with permission).

THE IMPORTANCE OF THE CONCEPTUAL MODEL

In relation to groundwater control, a conceptual model can be defined as “a simplified non-mathematical representation of a groundwater system to help understand and communicate groundwater conditions”. Further information on conceptual models can be found in Brassington and Younger (2010) and Baynes and Parry (2022).

A credible conceptual model is a key element of any assessment of groundwater control requirements, and it is good practice for the initial conceptual model to be prepared at the very earliest stage of developing a solution. The aim should be to develop a model that aids understanding of the problem being addressed, based on the data available at that time. The model should evolve by being improved as further data become available. As the statistician George Box once said, “All models are wrong but some are useful.” The objective in design is make the conceptual model more useful as the design progresses, with the aim of clearly communicating ground conditions and risks to the engineering decision makers.

One of the areas where groundwater control designers can make mistakes is focussing too early on assessing values of permeability, before the boundary conditions and hydrogeological variations (such as the presence of aquifers and aquitards) have been identified. Some examples of problems with conceptual models are discussed in the case histories later in this paper.

THE RISK OF EXTERNAL IMPACTS

Groundwater control has long been considered an activity with a significant risk of impacts beyond the boundary of the construction site (see Case History 4). The hydraulic gradient for a pumping system in a granular soil is relatively shallow, so the influence of a dewatering system sometimes extends to a considerable distance beyond the site boundary. It is likely to extend to a rather greater distance than the zone of direct influence generally associated with excavations, retaining walls and tunnels, where the maximum lateral extent of the settlement trough is generally equivalent to approximately the depth of the structure.

Lowering groundwater levels increases the vertical effective stress on the strata below the initial groundwater level, which inevitably results in the compression or consolidation and settlement of the ground. While the risk of ground settlements large enough to cause damage and distress to nearby structures can be a concern in soft soils, the risk can sometimes be overstated, particularly for dense granular soils or stiff clays where even significant lowering of groundwater levels for temporary works purposes may result in modest settlements. A sound conceptual model and assessment of structures is typically required to determine the level of risk involved.

In addition to potential settlement impacts, lowering of the groundwater level beyond the site boundary can adversely impact groundwater-dependent features or existing licensed abstractors, and can mobilise any existing groundwater contamination. These risks need to be considered, including mitigation measures where necessary, in any relevant environmental permitting process. It should be noted that the groundwater control design process often needs to be fairly advanced before it becomes apparent whether any concerns are potentially significant.

REGULATORY MATTERS

Groundwater control has unusual characteristics (relative to other geotechnical processes) because in many jurisdictions the pumping of groundwater for construction projects is a regulated activity. The permitting process is usually under the control of an environmental regulatory body that is part of either the national or provincial government for the location concerned.

This means that in many cases any significant groundwater pumping activity will require advance permission for both the extraction of groundwater and for its discharge back to the environment (including by artificial recharge). This puts additional constraints on pumped groundwater control systems, compared to some exclusion methods or fluid counter pressure methods. It is also important to recognise that groundwater exclusion schemes may sometimes require regulatory permissions, if the rates of groundwater pumping exceed the minimum limits set out in the regulations that apply at the location in question.

SOME CASE HISTORIES

CASE HISTORY 1 – PUMPING, EXCLUSION AND RECHARGE USED IN COMBINATION

The Thames Tunnel on the HS1 railway line (known as the Channel Tunnel Rail Link at the time of construction) passes under the River Thames east of London in twin 7.2 m internal diameter tunnels with lowest invert at -40 mAOD.

Ground conditions at the tunnel portals (on either bank of the river) comprise very soft alluvial clays and peat over highly permeable sands and gravels of the River Terrace Deposits, with permeability in the range 10^{-3} to 10^{-4} m/s, determined from pumping tests and correlations with particle size analysis. The gravels are underlain by the White Chalk Group. The River Terrace Deposits and the chalk were assessed to be in hydraulic connection and form a single aquifer, although it was possible that lower permeability structureless chalk existed at the strata boundary. In the central part of the river channel the aquifer is hydraulically connected to the tidal waters of the River Thames. On either shore the gravels are overlain by 10 to 12 m of Alluvium of low permeability, which form an aquitard above the confined aquifer of the chalk and River Terrace Deposits.

The groundwater control strategy for the approach structures used significant exclusion and pumping elements to match the ground conditions. The gravels were assessed to be significantly more permeable than the chalk, and weathering of the chalk meant that its permeability reduced with depth below the chalk/gravel interface. Therefore, vertical concrete diaphragm walls were installed to penetrate through the gravels and seal into the top of the weathered chalk. Pumping from an extensive array of dewatering wells was then used to lower groundwater levels within the area enclosed by the cut-off walls.

Even with the cut-off effect of the diaphragm walls, numerical groundwater modelling predicted significant external lowering of groundwater levels If this occurred, there was the risk of settlement damage to a neighbouring tank farm, caused by consolidation of the soft Alluvium. Artificial recharge was used as a risk mitigation measure, and an array of recharge wells (screened in the River Terrace Deposits) was used outside of the north approach structure to maintain groundwater levels and reduce settlement (Figure 2).

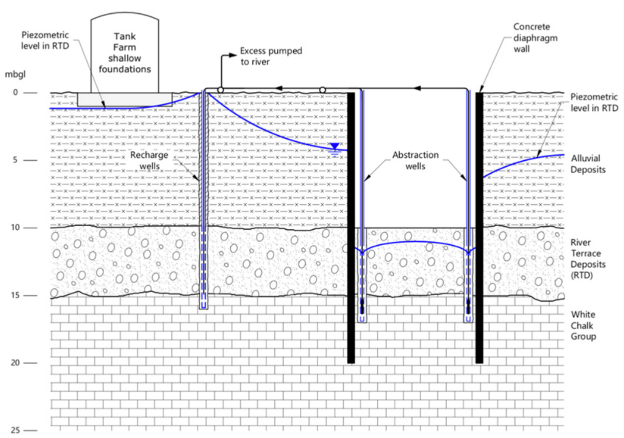


Figure 2: *Schematic cross section, including provision for external recharge at the northern approach, From Lawrence et al. (2025), adapted from Roberts & Holmes (2011)*

Other strategies were used for other parts of the project. The running tunnels used the fluid counter pressure method. The groundwater control strategy used for the cross passages between the running tunnels was ground treatment to exclude groundwater. The technique used was grout injection to form a 10 m long by 8m wide by 8 m high block of treated low permeability chalk through which the cross passage was excavated.

Further details of the ground conditions and groundwater control measures are given in Bevan et al. (2010).

CASE HISTORY 2 – USE OF GEOLOGICAL STRUCTURE TO REDUCE INFLOWS

The Channel Tunnel was constructed between England and France from the late 1980s to mid-1990s (Harris et al., 1996). The proposed vertical alignment of the tunnel was mostly through the Grey Chalk Group (formerly the Lower Chalk), a stratum that was not well characterised in terms of geotechnical or hydrogeological properties. Much of the tunnelling was through the West Melbury Marly Chalk Formation (formerly the 'Chalk Marl'), a material expected to be different in nature to the classic white chalks of the White Chalk Group, which were formerly known as the Upper and Middle Chalk (Mortimore and Pomerol, 1996).

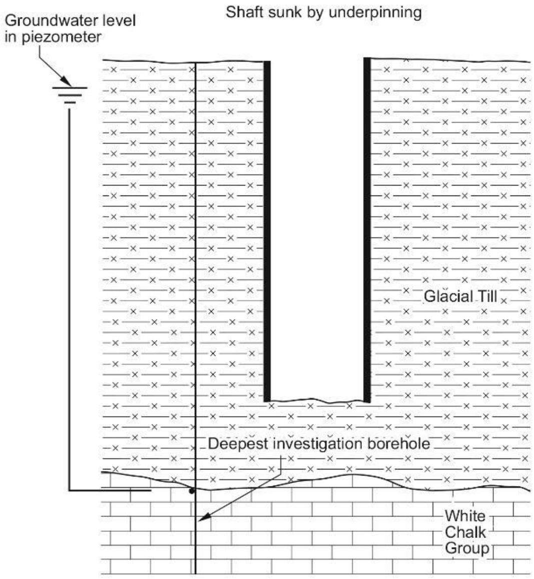
Investigations confirmed that calcium carbonate content of the chalk decreased and clay content increased with greater stratigraphic depth. In terms of geotechnical properties relevant to tunnelling, the lowermost zone of the chalk (immediately above the Glauconitic Marl) is often considered as a distinct geological unit – still colloquially known to some engineers as the Chalk Marl. As a tunnelling medium, this bed is typically less brittle and of lower permeability than the higher zones of the chalk, and has many attractive characteristics for tunnelling, including low rates of groundwater inflow. The vertical alignment of the Channel Tunnel was set to maximise the length of drive in this relatively benign material. This allowed tunnel drives from the English side to be successfully carried out by open face tunnel boring machines (TBMs) with relatively minor inflows of groundwater.

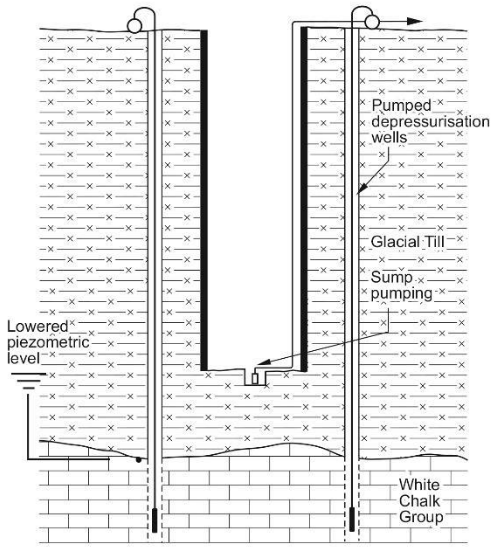
CASE HISTORY 3 – HYDRAULIC FAILURE OF THE BASE OF A SHAFT

A 19 m deep shaft of 6 m diameter was sunk by underpinning methods through a diamicton-dominated Glacial Till deposit of very low permeability. The shaft was sunk to final depth with minimal groundwater inflow (which was dealt with by sump pumping), and the base was completed in effectively dry conditions and a thin layer of blinding concrete was placed. A few days later the shaft was found to be full of water to just below ground level. The evidence indicated that a hydraulic failure had occurred; more than 500 m^3 of water had entered the shaft over a few days, despite the Glacial Till being of very low permeability.

Post failure review (Figure 3) indicated that a buoyancy uplift failure occurred in the plug of Glacial Till below the base of the excavation. This was caused by the presence of a confined chalk aquifer had not been identified by the original investigation boreholes, which were too shallow; hence the confined aquifer was not in the original conceptual model. The revised, post-failure, conceptual model led to a groundwater control strategy using eight 35-m deep pumped wells. The system was pumped at approximately 100 l/s to lower the piezometric level in the Chalk to 20 m depth. The flooded shaft could then be safely pumped out, and the disturbed material removed and the shaft base slab completed, albeit several months delayed.

The problems could probably have been avoided if a pre-construction desk study had identified the possible presence of the chalk aquifer below the Glacial Till, and if deeper investigation boreholes had been specified to prove the depth of the top of the potential confined aquifer; recommended good practice is for investigation boreholes to penetrate to at least 1.5–2 times the depth of the excavation (Cashman and Preene 2021). The incremental costs of these additional site investigation measures are likely to have been much less than the costs of the delays and disruption resulting from the failure.





Ground conditions assessed from post-failure investigations *Deep well pumped groundwater control system implemented post-failure*

Figure 3: *Schematic cross section through shaft (from Preene, 2021, with permission)*

CASE HISTORY 4 – EXTERNAL SETTLEMENT IMPACTS

Groundwater lowering by pumped wells creates hydraulic gradients toward the dewatered site, and can lower groundwater levels over a potentially wide area. This has the potential to cause impacts at significant distances from the construction site, much further than can result from most other geotechnical processes.

In this case history (Powrie, 1993) a small 4.3 m deep excavation was dewatered by a wellpoint system. After around 3 weeks of pumping, properties up to 500 m distant began to report structural damage. Subsequent analysis revealed that the ground conditions comprised approximately. 4 m of peat and soft alluvial clay, over glacial sand and gravel, which was the stratum being pumped by the wellpoints. The glacial sand and gravel formed a confined aquifer, below an aquitard comprising the soft clay and peat. Lowering of groundwater levels in the gravel caused downward drainage of the aquitard, leading to consolidation settlements. Had this been included in the conceptual model, this should have identified the need for an assessment of the risk of structural damage that could result from consolidation settlement, requiring consideration of the likely magnitude of settlements and the presence and nature of structures within the zone affected. The results of this may have prompted designers to consider alternative groundwater control strategies, such as groundwater exclusion, or the use of mitigation measures such as artificial recharge.

It is unusual that settlement damage was reported at such great distances from the pumping system; the theoretical distance of influence for such a small drawdown would not typically be so large. The very large extent of the zone of drawdown probably indicates that the gravel aquifer is bounded laterally, rather than being of effectively infinite extent. Furthermore, it was reported that the most distant property at which settlement damage was claimed coincided exactly with the edge of the peat deposit on the geological map of the area (Figure 4). It is highly likely that a thorough conceptual model would have identified these aquifer and strata boundaries, and helped the designers develop a strategy to minimise these potential impacts.

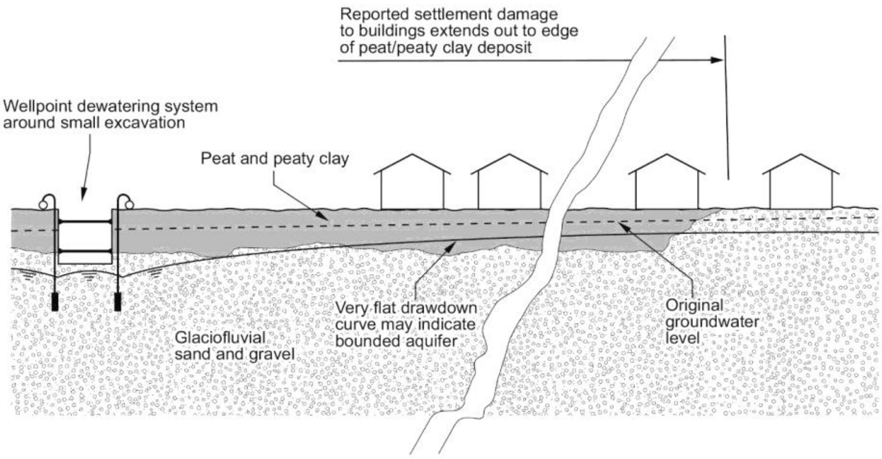


Figure 4: *Conceptual model of potential ground settlements caused by a wellpoint dewatering system (from Preene, 2021, with permission)*

SETTING USEFUL OBJECTIVES FOR GROUNDWATER CONTROL DESIGN

Groundwater control is required at the very start of most engineering projects that involve work to any significant depth below ground level. It is often one of first geotechnical processes required on site, and is the first that must be proven effective for significant construction work to proceed. Therefore, there is a risk that problems or delays caused by groundwater at this early stage can delay the whole project. However, the design, installation and operational costs of groundwater control systems are typically only a very small part of the overall construction costs of an infrastructure project – a study by Roberts and Deed (1994) showed that the direct cost of pumped well groundwater control systems was typically less than 1 per cent of total costs on a large civil engineering project. Roberts and Deed (1994) highlighted that the cost of resultant delays from a poorly performing system can be many times greater than the direct cost of the groundwater control works themselves.

When defining key objectives for groundwater control designs, the author considers that the primary focus should not be on minimising the cost of groundwater control, or even attempting to develop a lean and efficient system. Rather, the focus should be on ensuring certainty of outcome (i.e. effective control of groundwater). Because if hydrogeological conditions are sufficiently different to those assumed in design, and as a result the strategy must be changed or modified, then significant delays can result. The cost of those potential delays will be much larger than the cost of including additional groundwater control measures (such as more pumped wells, deeper cut-off walls or the use of artificial recharge to mitigate external impacts) at the outset, to increase confidence that the system will be fully effective when commissioned. This requires a through and relevant ground investigation, a realistic conceptual model that is updated as more data are gathered, and sensitivity analyses in design to assess the impact of credible ranges of possible variations in parameters and boundary conditions.

CONCLUSIONS

Groundwater control can form a key part of the temporary works for infrastructure projects. The scale of these projects can present challenges including: very large lateral extent of the works; significant depth of excavations; the presence of nearby sensitive structures or water-dependent features which may be affected by the drawdown effects of groundwater lowering; and the potential for increased regulatory scrutiny. These challenges can be overcome by selecting an appropriate groundwater control strategy. This requires a through ground investigation, a realistic conceptual model, and sensitivity analyses to assess the impact of credible ranges of possible variations in parameters and boundary conditions.

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DEVELOPING PRACTICAL ENGINEERING SOLUTIONS TO DEWATERING CHALLENGES

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ABSTRACT

This paper uses the experience of the construction of the Kildare Town Bypass, now part of the N7, which was the largest dewatering project carried out in Ireland in recent times, to assess the practical solutions adopted and to compare the values of the coefficient of permeabilities interpreted from site investigation data with those estimated from the site experience. The paper also looks at the extent of tidal variations behind marine boundaries and to methods that can be used to benefit from the limited time of peak level.

Key words: *dewatering, coefficient of permeability, tidal boundaries.*

INTRODUCTION

The design of construction dewatering systems presents many interesting challenges that have to be overcome to enable work to proceed productively and safely. Dewatering is a colloquial term that in common usage generally includes groundwater control measures. It is not as straightforward as it appears, as it must consider not only the ability to remove water from the soil but also the ability of available equipment to remove this water, the extent of drawdown, available discharge locations, the stability of the base and sides of excavations, methods of preventing of erosion of material and of course the time effect of drawdown on the surrounding area, which can be very extensive.

This paper looks at the experience of the dewatering methods adopted for the Kildare Town Bypass, the largest dewatering project ever carried out in Ireland in recent times, to illustrate the practical methods adopted to dewater a complex glacial aquifer. This experience is also used to assess the reliability of methods of estimating the coefficient of permeability. The use of advanced numerical models is discussed. The paper also discusses the extent of tidal variations behind marine boundaries and methods that can be used to benefit from the limited time of peak water levels.

EXPERIENCE FROM KILDARE TOWN BYPASS

The experience of constructing the Kildare Town Bypass, now part of the M7 motorway, offers an example of a large-scale dewatering project in a glacial aquifer and shows the advantages of sump pumping over deep wells. It also offers the opportunity to assess the reliability of predicting the coefficient of permeability from geotechnical data. This was a controversial project at the time because of the risk that long term drawdown of the water table was deemed to have on hydrogeological conditions and the special ecology at Pollardstown Fen which was 5km distant. The author developed a groundwater control system which limited the long term drawdown at the road to about 1.75m above road level rather than 1.5m below road level which would be standard practice for road drainage (Farrell and Coppinger, 2004). This was achieved by 'tanking' a 3.5km section of the road – see Figure 1, and constructing a drainage system with controlling weirs to limit the water pressures around the road – see Figure 2. Excavations of up to 7m below the water table, however, were required during construction.

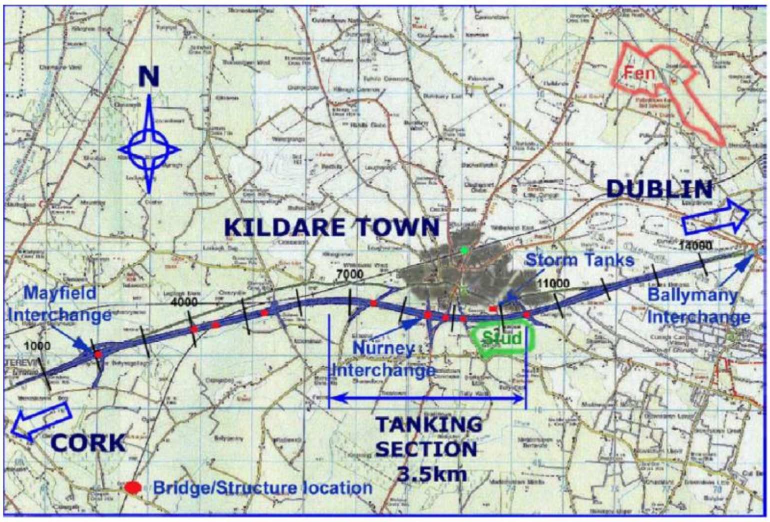

Figure 1: *Location of the Tanked Section of the Kildare Town Bypass*

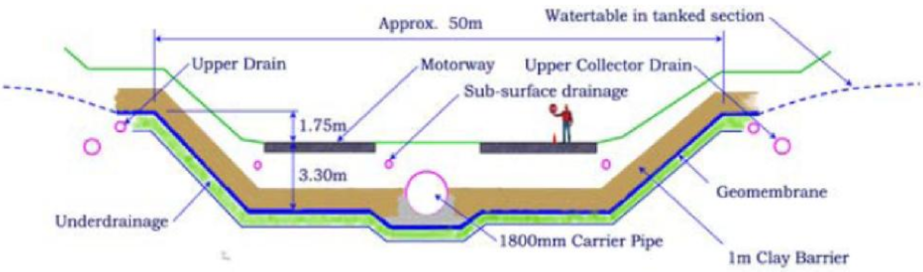

Figure 2: *Illustration of the construction of the Tanked Section*

The scale of the construction dewatering can be appreciated from the discharges measured during the as shown on Figure 3. The road was constructed in stages from west to east, initially in 500m lengths but this was increased to 1000m sections in May 2002 to limit the duration of dewatering. A change in the ground conditions let to the discharge nearly trebling over the last quarter (from Ch 96+00) to about 550 l/s and this level of discharge continued for about 4 months. Initially the Contractor attempted to dewater using a series of deep wells but this was quickly abandoned as inefficient and a system of large sump pumping was adopted due to its significantly greater discharge capacity– see Figure 4. The depositional environments of glacial aquifers can be very complex and this results in very variable ground conditions as is illustrated on Figure 5. Although sump pumping was used, the removal of fines was generally not an issue, however filter arrangements were applied where necessary. Prior to construction, the permeability of the aquifer was assessed from the particle size distribution analyses (PSD) using Hazen (1991) and others– see Figure 6, from variable head tests (VHT) – see Figure 7 and from pumping tests – see Table 1. The k values from PSDs tended to give excessively high values whereas those from VHT were very variable with those from rising head tests being generally higher than those from FHT – see Figure 8. k values were not recorded when the water level in the boreholes could not be raised in VHTs with the methods used on site and the absent of these values distorted the results. The k values from pumping tests were more consistent – see Table 1 and by far the most reliable. For comparison with site experience, assuming steady state conditions, using the Theim/Dupuit equation (Misstear et al., 2006) and the measured drawdown at Tully Bridge (Ch 91+70), a k= 1.0 to 2.0x10^{-4} was estimated (MacCarthy 2008). A similar analysis of the excavation between Ch 69+00 and 74+00 gave k values of between $3.5x10^{-4}$ and $6x10^{-4}$ m/s. The extent of the drawdown at Tully Bridge was about 1km, significantly greater than the 150m estimated using the empirical relationship R_o = 1000 to $3000\Delta H(k)^{0.5}$ (k in m/s).

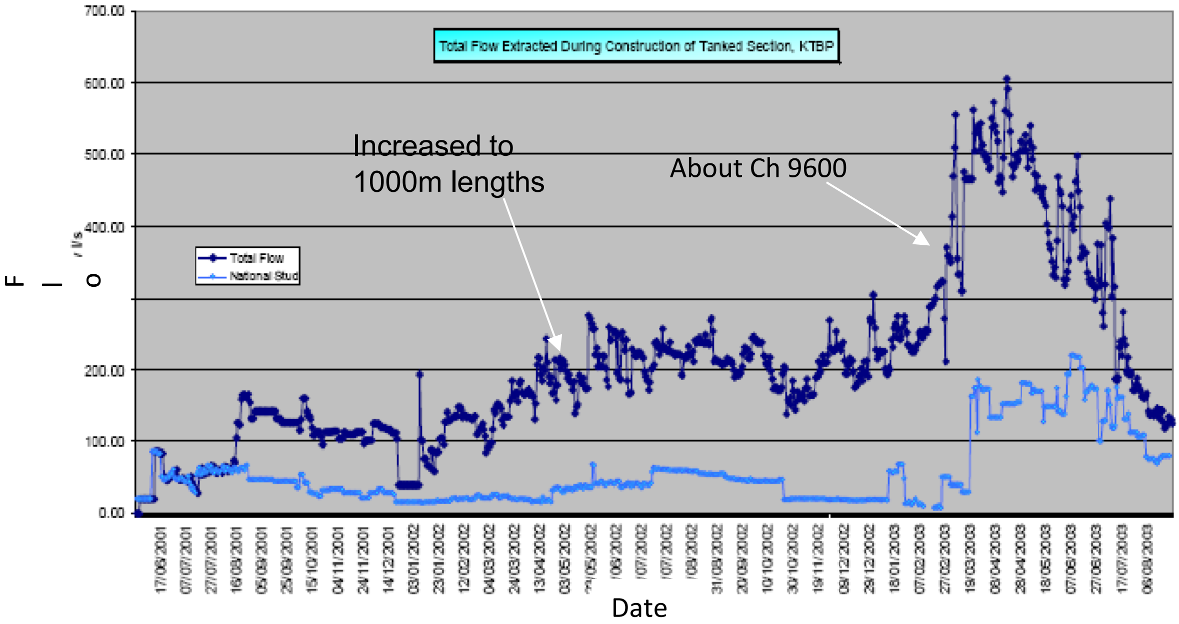

Figure 3: *Measured discharge from excavation versus time.*

Figure 4: *Large scale sump pumping.*

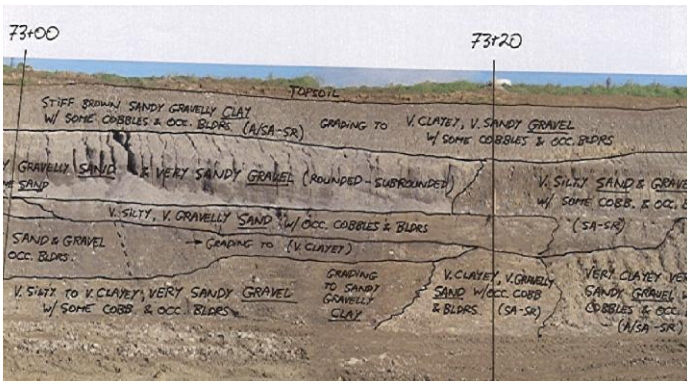

Figure 5: *Variable ground conditions of glacial aquifer*

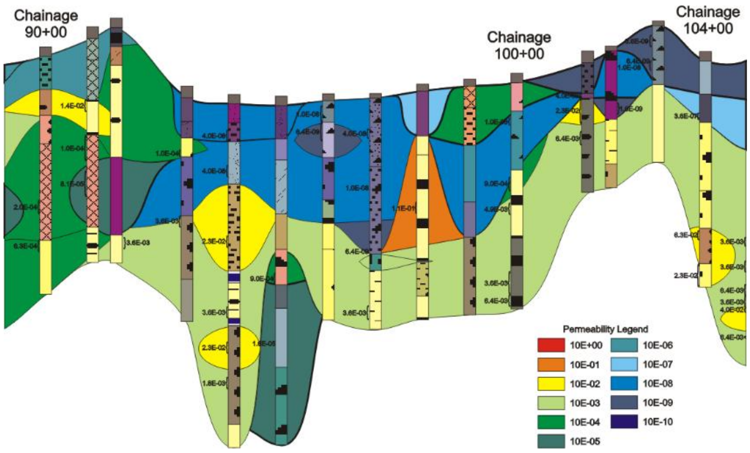

Figure 6: *k from PSDs (MacCarthy, 2008)*

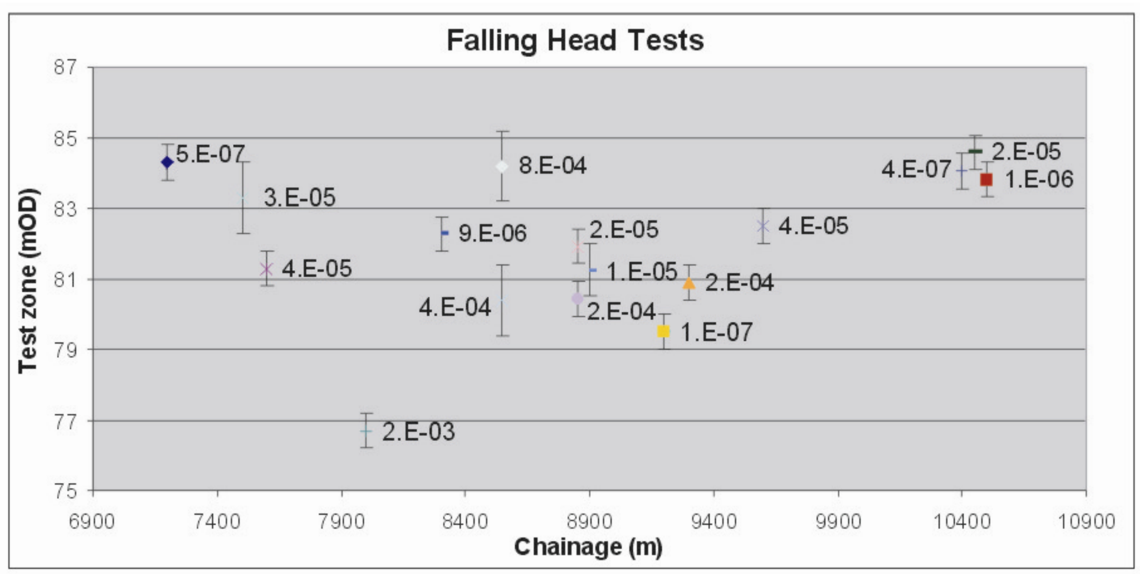

Figure 7: *k from Rising Head tests*

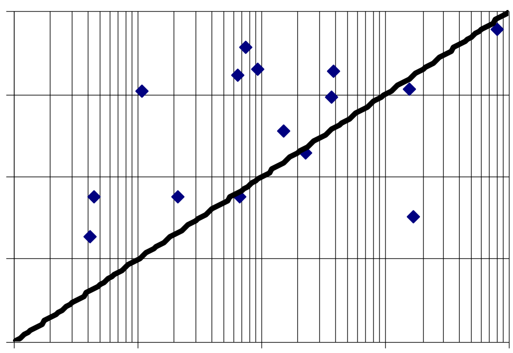

Figure 8: *Rising v Falling head VHTs*

Table 1: k from pumping tests

Location	Pump test (m/s)	Recovery test (m/s)
Mooretown Bridge Ch 71+00	$2.1x10^{-4}$	$9.2x10^{-3}$
Nurney Bridge Ch 84+15	$1.6x10^{-5}$	$7.7x10^{-4}$
Greyabbey Bridge Ch 88+60	$5.8x10^{-5}$	$1.8x10^{-4}$
Sewage Treatment Works (~9,550)	2.2x10-4	$2.9x10^{-4}$
Frenchfurze Road Ch 104+50	3.5x10-4	

A considerable amount of groundwater monitoring data was carried out before and during the works and this allowed the hydrogeological behaviour of the Mid Kildare Aquifer be studied using advanced numerical methods, including MODFLOW and FEFLOW (MacCarthy, 2008). This required the development of a conceptual model of the aquifer and the input of appropriate parameters for vertical and horizontal permeability, specific yield, specific storage and recharge. A reasonable estimate of the time varying response was achieved – see Figure 9, however this level of analyses did not contribute significantly to the selection of dewatering methods on site.

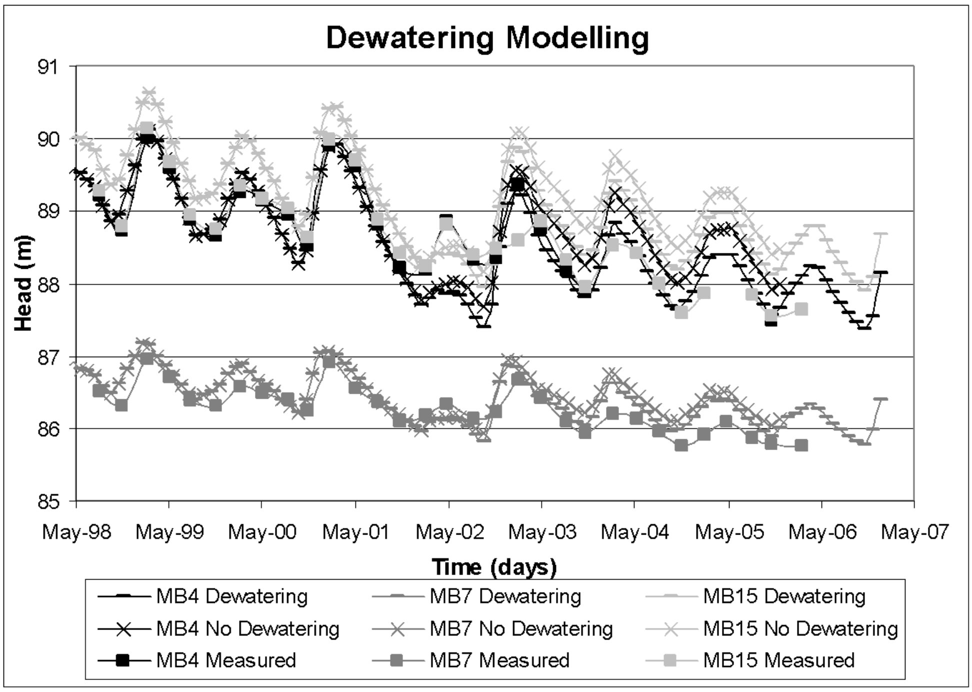

Figure 9: *Comparison of recorded and estimated time varying response at one monitoring station.*

RIVER AND TIDAL BOUNDARIES

Tidal and river boundaries are a frequent feature in dewatering projects in this country. Two aspects of this are interesting, firstly that the proximity to a water source may not be a dramatic as initially imagined and the other is the significance of storativity in the extent of tidal variation. Verruijt (1982) showed that the tidal amplitude was reduced to 5% when $\lambda x=3$ – see Figure 10. The symbol $\lambda = (\omega S/2H_o k)^{0.5}$ where $\omega = 2\pi/\tau$ α, S is the storativity and τ = period which for a semi-diurnal tide is 12 hrs. This assumes one-dimensional flow and a free boundary. Farrell(1994) extended this closed form analysis to include flow through leaky structures. Putting in typical properties for a sand of $k=10^{-5}$ m/s and S = 0.1 gives x = 16m for a semi-diurnal tide with 2m amplitude with an open boundary, thus showing the limited extent of tidal effects in an unconfined aquifer. The opposite applies to confined aquifers, where the tidal variation can extend a considerable distance inland.

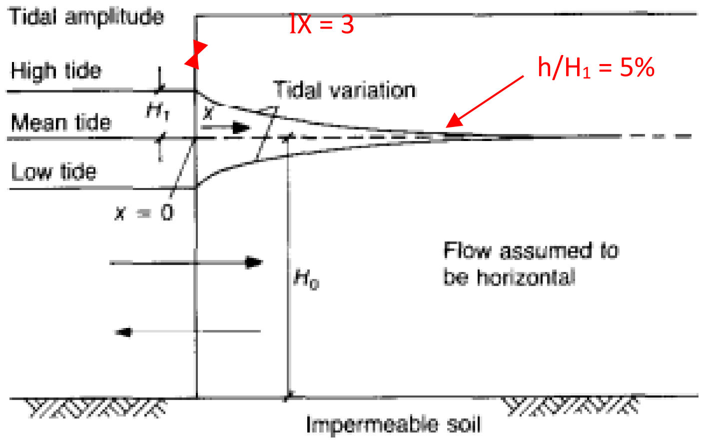

Figure 10: *Extent of tidal variation*

The effect of a river boundary on an excavation can be estimated using the Theim/Dupuit equation when modified using the principle of image wells. This gives the equation for a confined aquifer of thickness D of

$$H - h = Q_w Ln(\frac{2L}{r_w})/(2\pi kD)$$

where

H = initial height of groundwater level above bottom of aquifer
L = distance of line water source from excavation
h = level above bottom of aquifer to which the WL is to be drawn down at the excavation
Q_w = discharge from excavation
k = coefficient of permeability
r_w = equivalent radius of excavation

An interesting design situation arose when developing the dewatering system for the basement of the Cork Courthouse in Anglesea Street, Cork city – see Figure 11. The ground conditions comprised made ground, over peat, over a gravel aquifer. The dewatering system had to be designed to limit drawdown in the surrounding area at low tides to prevent settlement in adjoining premises and yet was required to have sufficient capacity to handle high river levels during river surge situations, a situation which actually did occur during the works. The aquifer was confined, which extends the tidal influence significantly. The flow pattern around the excavation at high tide is indicated on Figure 13. A system of deep wells was installed – see Figure 14, to cater for the normal high tide that occurred in the river but rather than design the system for an extreme river surge, advantage was taken of the temporary water storage given by slight flooding of the excavation for the limited period of the surge to reduce the number of wells required – see Figure 14.

Figure 11: *Locations of New Courthouse on Anglesea St. Cork*

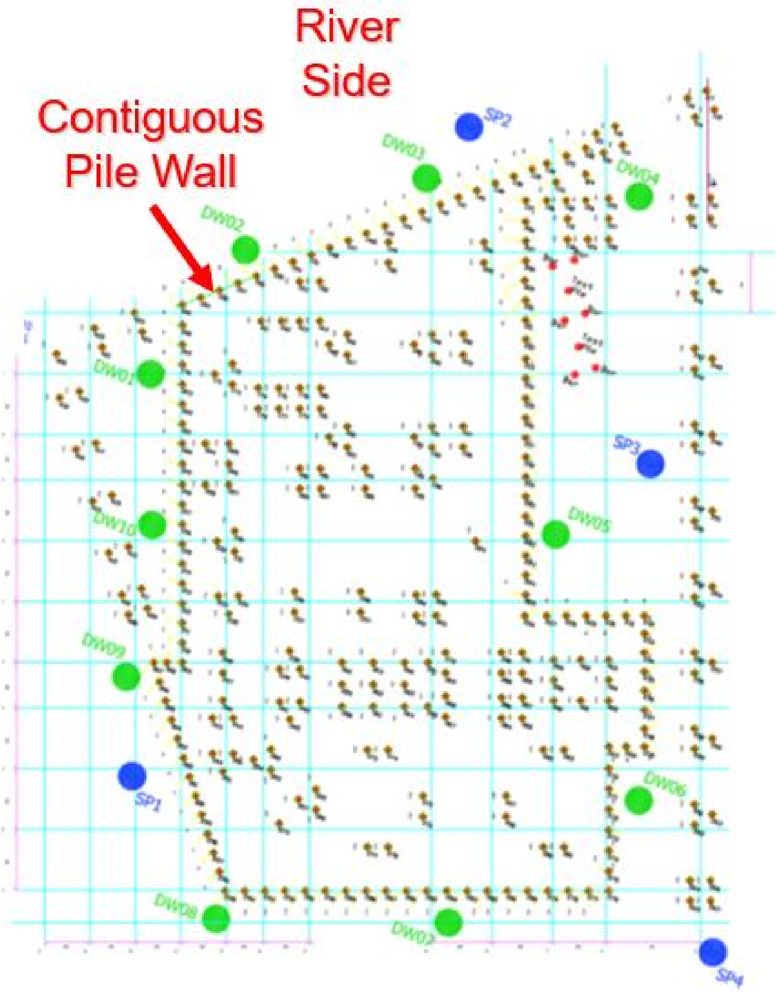

Figure 12: *deep well strategy adopted*

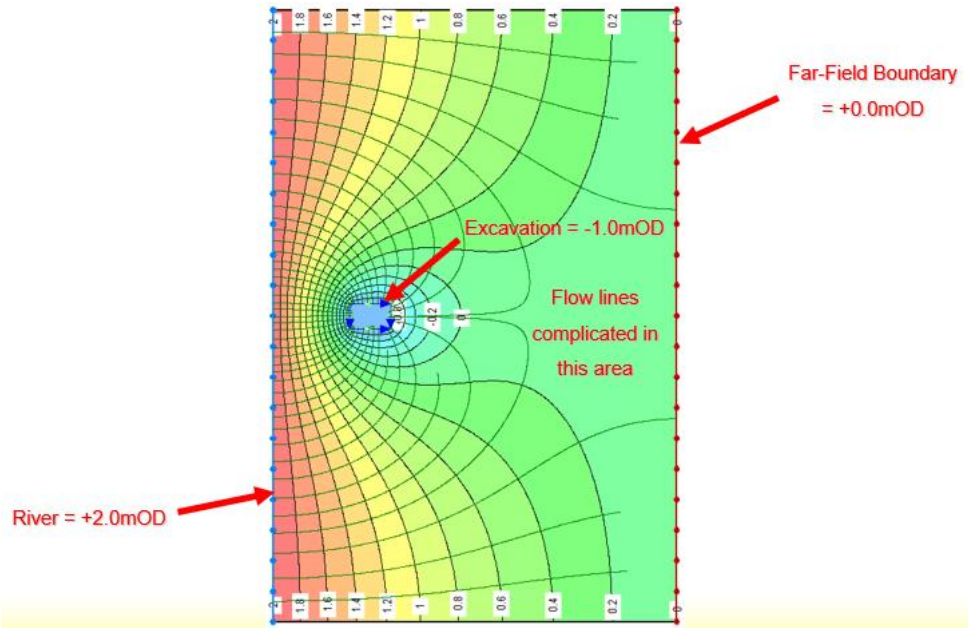

Figure 13: *Flow pattern into excavation at high tide (from Seep/W)*

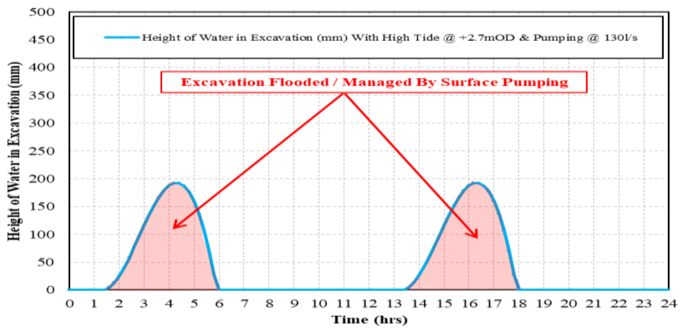

Figure 14: *Expected flooding of excavation during river surge*

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SESSION II

CASE HISTORIES: SUBSIDENCE INDUCED BY GROUNDWATER PUMPING AND LOWERING

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ABSTRACT

The paper presents some case histories from projects in Cork and Dublin where there were some concerns regarding the possible effects on adjacent buildings caused by dewatering induced ground settlements. The paper focuses on consolidation issues rather than subsidence caused by removal of fines from the ground. Three of the Cork case histories showed that only negligible settlements were recorded. The fourth was located at a site where there were no soft alluvial layers present. The reason for the low settlements is likely largely due to the induced stresses being lower than the preconsolidation stress of the material. Careful ground investigation with high quality sampling is essential for such assessments to be made. In general the ground conditions in many places Dublin are very good so there are few well documented examples of subsidence induced by groundwater lowering. The Dublin Tunnel case history does show that these settlements can occur faster than expected due to inter-connectivity of gravel lenses in the material.

Key words: *settlement; groundwater; alluvium; glacial deposits; ground investigation*

INTRODUCTION

The purpose of this paper is to present some Irish case histories on the topic of subsidence induced by groundwater pumping and lowering. A distinction needs to be made between:

- settlement due to consolidation which can be significant in soft soils and can be is minimal in stiff / dense overconsolidated soils and,
- settlement due to pumping of fines/ground loss from sump pumping or poor filter design.

The former can only be mitigated by recharge and / or cut-offs whereas the latter is entirely avoidable by good practice (Personal communication Toby Roberts, W.J. Groundwater, March 2025). This paper deals with issues related to consolidation settlements only. Case histories are given for several sites, with contrasting ground conditions, in the Cork and Dublin areas.

THEORETICAL BACKGROUND

The theoretical background to the topic lies in Archimede's principle which states that objects which are submerged will be "lighter" and that the buoyancy force on a submerged object will equal the weight of the displaced water. In geotechnical engineering terms a reduction in water pressure will lead to an increase in the vertical effective stress (σ_v') which in turn will lead to extra stresses being placed on the grain structure of the soil and hence compression will occur.

Assuming that the soil is in its virgin condition, i.e. there have been no changes to the soil since it was deposited (in geotechnical terms the soil is "normally consolidated"), the calculation of the likely settlement (Δ) is relatively straightforward using the expression:

$$\frac{\Delta}{H} = \frac{C_c}{1+e_0}\left[\log\frac{\sigma`_v+\Delta\sigma`_v}{\sigma`_v}\right] \quad (1)$$

<u>where:</u>

H = the layer thickness,

C_c / 1+ e_0 = compression index

e_0 = void ratio = wG_s (w = water content, G_s = specific gravity)

$\Delta\sigma_v'$ = change in effective stress

The change in effective stress can be determined from the predicted drawdown in the water level outside the site. Perhaps the only difficult parameter is $C_c/1+e_0$ for which oedometer testing is required. However Mc Cabe et al. (2014) have published a useful correlation between $C_c/1+e_0$ and water content, for Irish soft soils, which can be used in the absence of detailed laboratory tests (Figure 1). In many cases the soil may not be normally consolidated. It may be lightly overconsolidated and the calculation detailed above will be conservative. This point will be addressed later. Preene (2000) also provides some useful guidance on the topic.

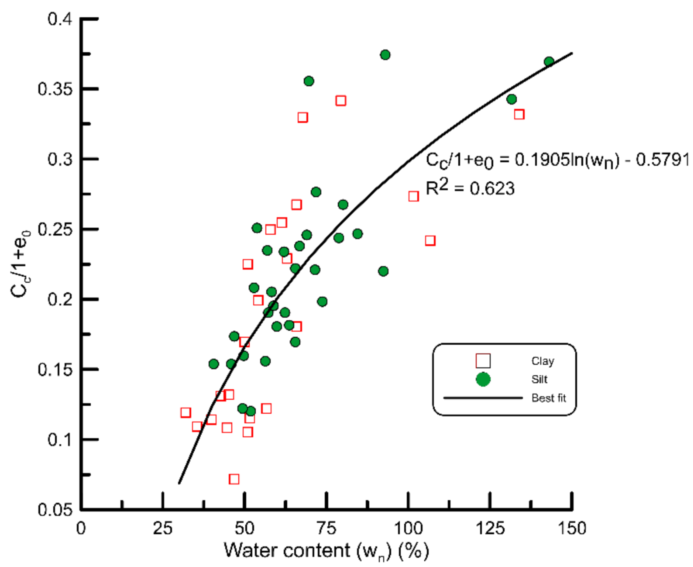


Figure 1: *Compression index versus water content for Iirsh soft soils (Mc Cabe et al. 2014)*

Preene (2000) points out that the zone of influence of the effects of drawdown induced settlement can be much bigger than for tunnels or excavations. The latter activities can influence an area a small number of times the excavation depth. However the effects of water level drawdown can be much more significant. For example Powrie (1994) details a case history where damage was recorded 500 m from an excavation.

CORK CASE HISTORIES

GROUND CONDITIONS

Ground conditions in the Cork City area are relatively well known (M. Long et al. 2015; Curtis and Long 2023). Cork is also known as Corcach mór Mumhan (the great marsh of Munster) which gives a good clue as to the likely ground conditions. The deep River Lee "gorge" was infilled with glacio-fluvial sands and gravels towards the end of the last glaciation. The valley was later infilled with estuarine clay, silt and peat forming a complex "braided" river system with the many river channels flowing around a series of marshes. The final development of Cork came about as sea level steadied some 6000 years B.P. Many waterways were infilled by 18th Century planners (e.g. Grand Parade, South Mall and St. Patrick's St) leaving today but the North and South Channels of the River Lee.

A very useful recent contribution to ground conditions in Cork is by Beese (2019) who used available data from engineering boreholes, archaeological excavations etc. to develop a map of the thickness of these estuarine deposits in Cork, as shown in Figure 2.

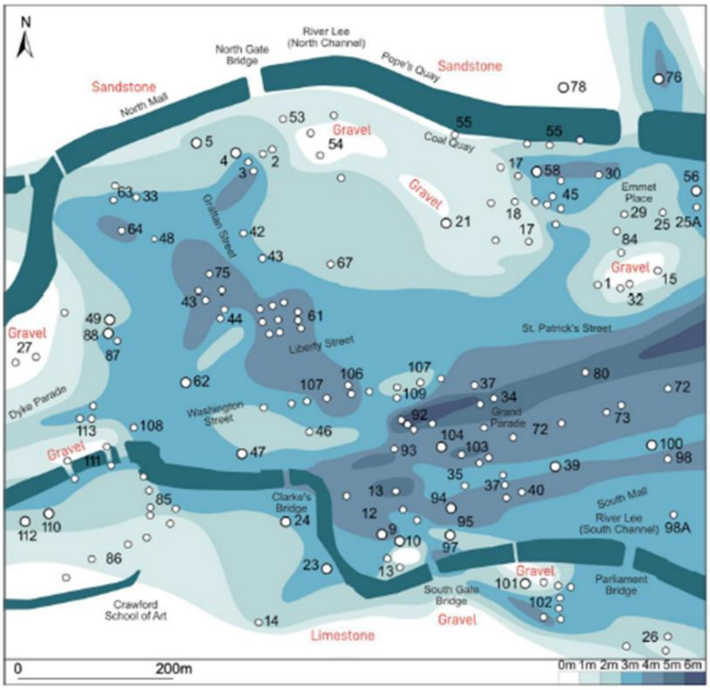


Figure 2: *Thickness of estuarine mud in Cork city centre (Beese 2019)*

AVAILABLE CASE HISTORIES OF SETTLEMENT MEASUREMENT

There is only limited data published for water level drawdown induced settlements of buildings in Cork. Data has been published by Holmes and Roberts (2005) for the Lapps Quay development and by M. Long and Roberts (2008) for the Beasley St. Project. Additional data is available for the 1 Albert Quay project. Some discussion will also be given on the Tyndall Institute development.

1 Albert Quay

An image of the completed 1 Albert Quay project is shown on Figure 3. Ground conditions and an outline of the basement works are shown on Figure 4. Ground conditions are typical for Cork with about 2.5 m of made ground, overlying 2 m of alluvium, over fluvio-glacial and then glacial gravels. The 6.5 m deep excavation was supported by 13 m long sheet piles. This length was chosen to provide some penetration into the denser deeper glacial gravels which were known to have lower permeability than the upper fluvio-glacial gravels. Water levels inside the site were controlled by a series of deep wells located around the site perimeter.

Figure 3: *1 Albert Quay, Cork*

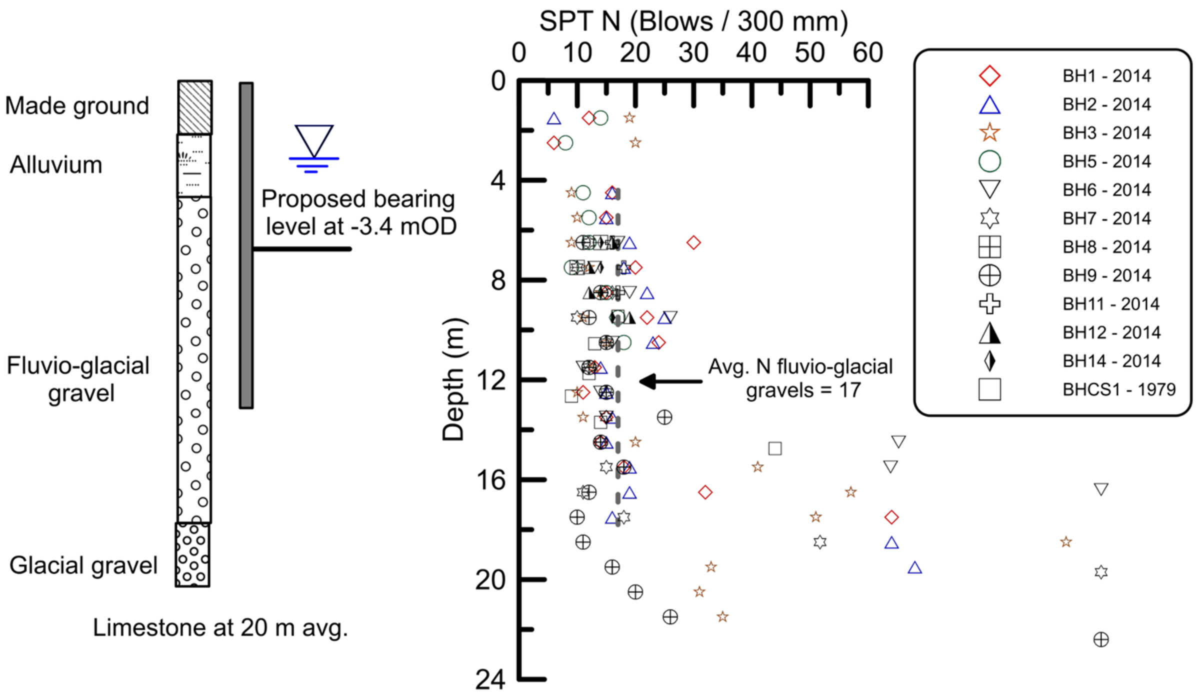


Figure 4: *1 Albert Quay ground condiitons and outline of basement works*

External ground water levels (i.e. just outside the sheet piles) were monitored during the works and it was found that typically the water table was reduced by some 1.5 m. The alluvium has average water content of about 70% and density of about 1.6 Mg/m^3. Using these values, Equation 1 and the soil properties shown on Figure 1, the estimated settlement is some 33 mm.

Measured settlements using a precise level, with a stated accuracy of ±0.3 mm, for various buildings in the vicinity of the site, are shown on Figure 5. More or less no settlement was recorded. It is not clear what the foundations of all the buildings comprise but the Sextant Pub and several of the adjacent buildings were founded at shallow depth on the made ground or alluvium.

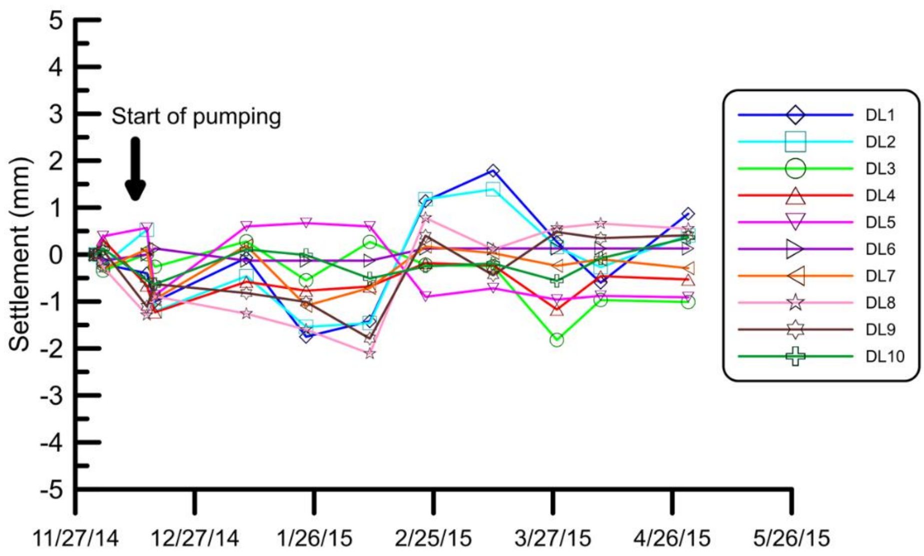


Figure 5: *1 Albert Quay – settlments of adjacent structures*

Beasley St. (M. Long and Roberts 2008)

Some details of the Beasley St. development are given by M. Long and Roberts (2008). Of significant concern were important structures around the perimeter of the site, like the Crosbie Holdings structure shown on Figure 6.

Figure 6: *Beasley St. development – adjacent structures*

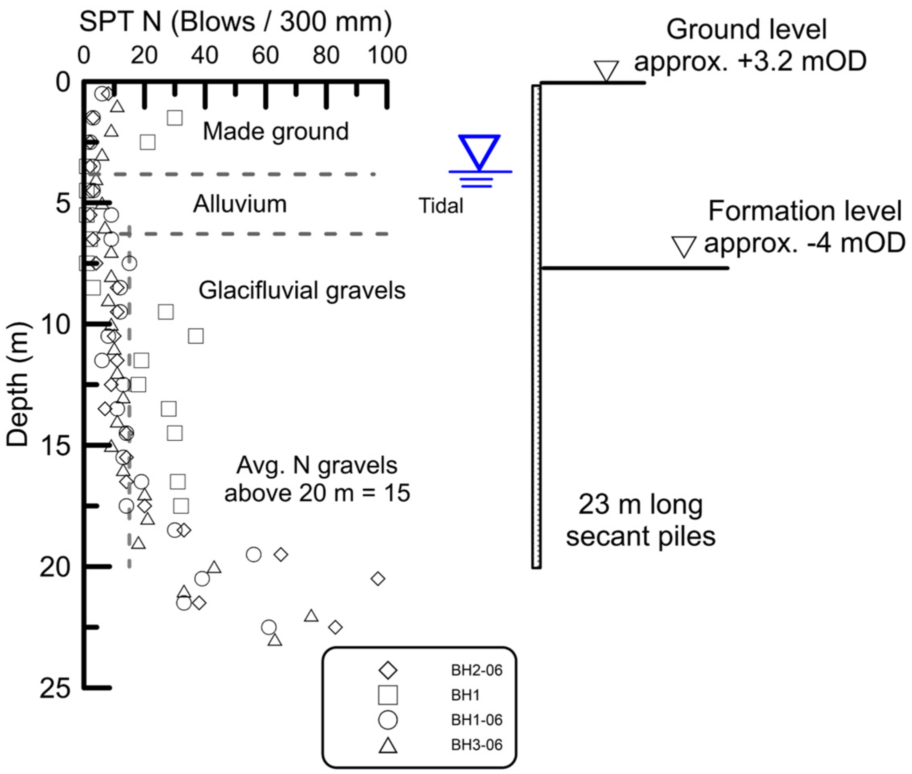


Figure 7: *Beasley St. – ground conditions and basement works*

The ground conditions, basement works, details of pumping system etc. used at Beasley St. were very similar to those employed at 1 Albert Quay (Figure 7). Perhaps the biggest difference was the use of 22 m long secant piles as the retaining structure rather than sheet piles which were used in most of the Cork basement works (M. Long et al. 2015).

Recorded settlements were very small – perhaps close to the accuracy of the monitoring system used (Figure 8). Settlement monitoring points were on a range of buildings, some of which are lkely to have been founded on the gravels but some also on the made ground or alluvium.

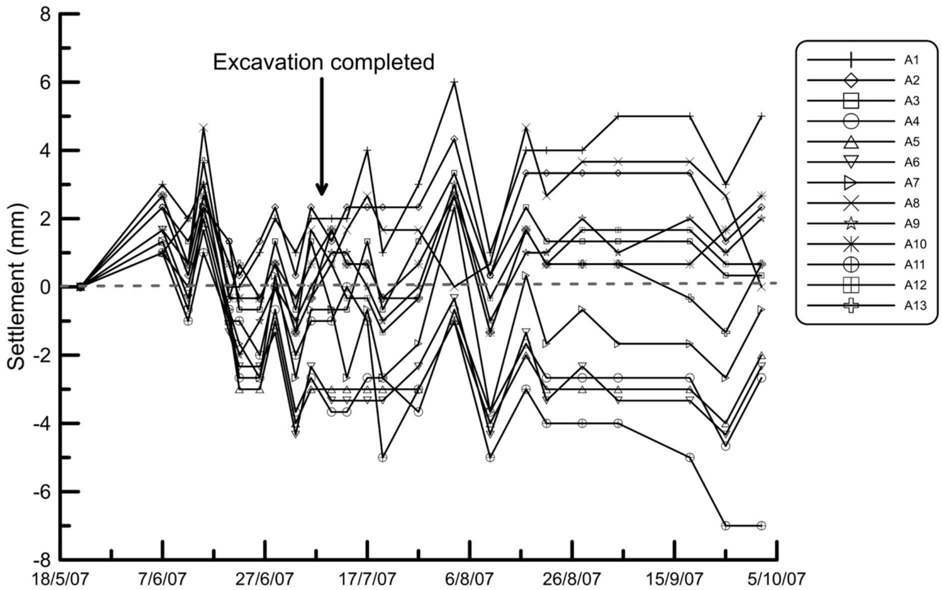


Figure 8: *Beasley St. – measured settlement (M. Long and Roberts 2008)*

Lapps Quay (Holmes and Roberts 2005)

The dewatering works at the Lapps Quay development have been described in detail by (Holmes and Roberts 2005). Of particular concern here was any impact the dewatering would have on the old Port of Cork building located adjacent to the site, see Figure 9. Other structures were also potentially vulnerable.

Figure 9: *Lapps Quay development (Killeen 2008). The old Port of Cork building is shown on the top left of the image*

Conditions at Lapp's Quay were again very similar to those at the other two sites. Perhaps the gravels are more competent with higher N values. Also the sheet piles are somewhat longer than at 1 Albert Quay.

Settlement monitoring again showed no appreciable movements occurred. All measurements were within the accuarcy of the recording instruments. It is likley however that the Port of Cork building was located on the gravels.

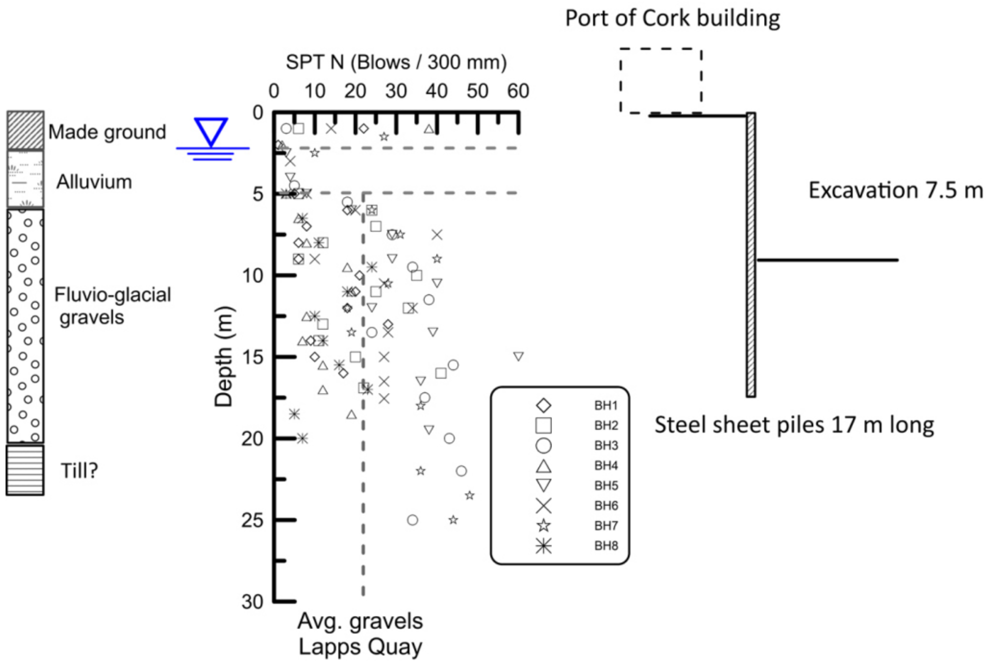


Figure 10: *Lapps Quay – ground conditions and basement works*

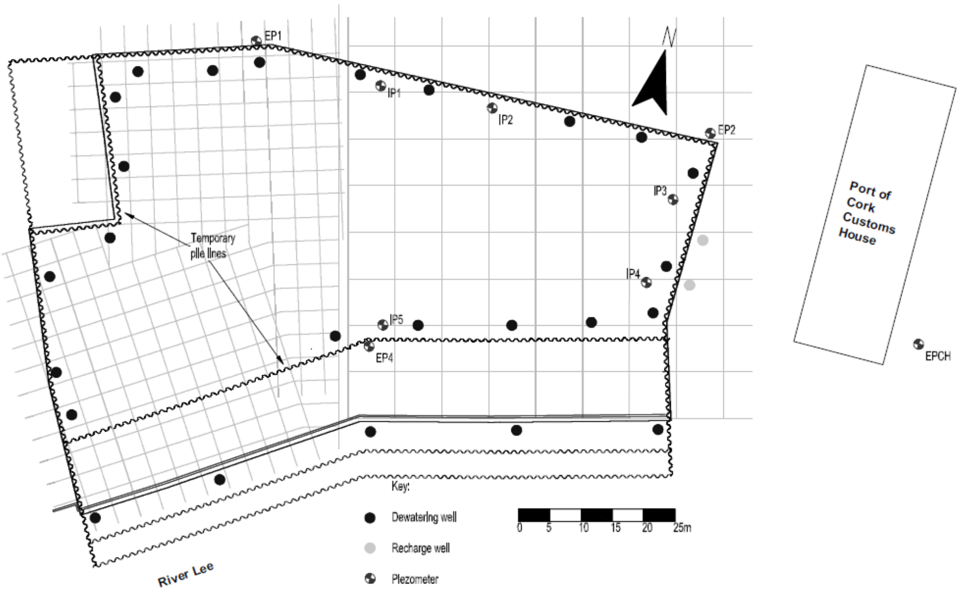


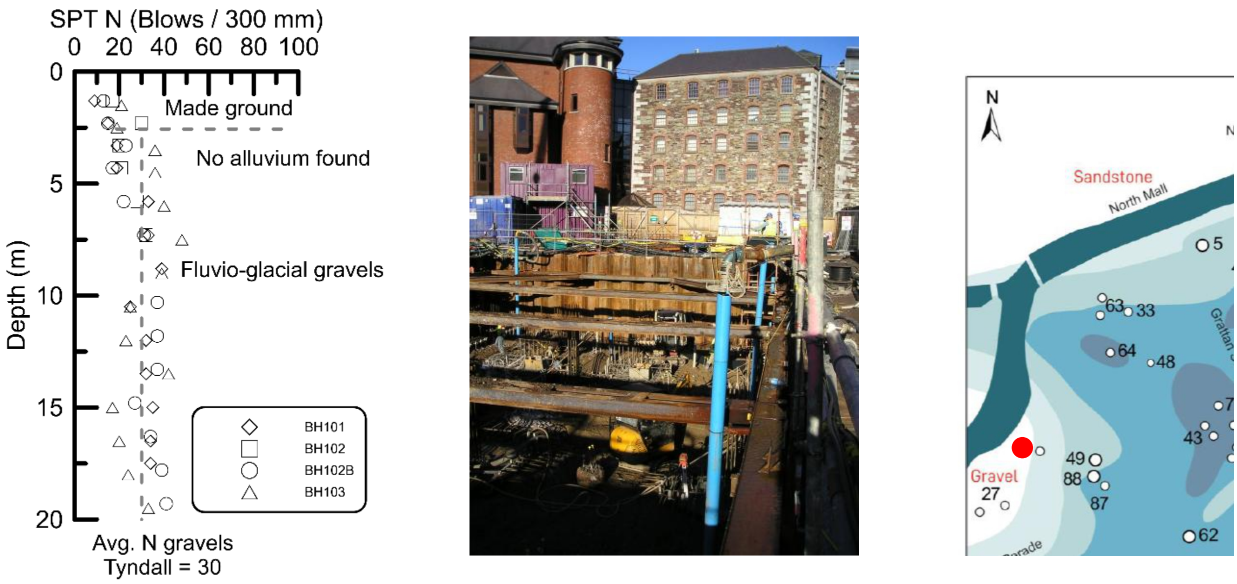
Figure 11: *Lapps Quay – site layout showing wells and instrumentation (Holmes and Roberts 2005)*

A feature of the Lapp's Quay development was that recharge wells were included in the vicinity of the Port of Cork building, see Figure 11. Holmes and Roberts (2005) report on a recharge trial that was carried out in the two recharge wells. Some of the abstracted water from elsewhere was fed to the wells. The monitoring showed a clear response of the external water levels due to the recharge. However the magnitude of the rise is difficult to quantify due to the tidal response. At various stages during the trial the recharge wells had to be redeveloped due to a drop in capacity because of iron staining and clogging. The trial showed that recharge was considered a viable option although the presence of dissolved iron in the groundwater would have led to a significant maintenance effort. As very little settlements were measured the recharge system was ultimately not implemented.

Tyndall Institute, UCC

Details of this project are shown on Figure 12a. The concern here was the old UCC "Lee Maltings" / NMRC (National Microelectronics Research Centre) buildings as shown on Figure 12b. Conditions were very similar to the other sites described above, except that no alluvium was present as the site is located on an old channel of the River Lee and not on a marsh. This is confirmed by the work of Beese (2019) as shown on Figure 12c. No detectable movements of the buildings were recorded.

This case history shows that simple desk studies can provide very valuable information.



(a) (b) (c)

Figure 13: *Tyndall Institute, UCC (a) site layout, (b) adjacent buildings and (c) snip from Beese (2019)*

WHY WERE THE MEASURED MOVEMENTS SO SMALL?

The simple calculation outlined above assumed the soil was “normally consolidated”, i.e. it had not experienced any change in its stress state since it was originally deposited and the current stresses are the maximum it has experienced. This is a very conservative assumption. The reality is that soil has a “memory” and the engineering properties will be a function of its stress history. In the past the Cork alluvium has been subjected to repeated load cycles mostly due to tidal cycles but also due to other human influence. This will give the soil a “prestress” similar to a prestressed concrete beam. The idea of a prestress is that if the beam is loaded up to this prestress level it will not settle appreciably as it has previously experienced and dealt with this load.

In geotechnical terms this is called the “preconsolidation stress (p_c’)”. If the load on the soil does not exceed p_c' then the resulting settlements may not be significant. Preconsolidation stress can be determined from a laboratory oedometer test. Unfortunately the determination of p_c' is very sensitive to sample disturbance effects and the best possible sample must be used for the purpose. The effects on sample disturbance on a Norwegian soft clay are shown on Figure 14 (M. Long, El Hadj, and Hagberg 2009). A comparison is made between a high quality Sherbrooke block sample and a relatively crude 54 mm piston sample. The block sample has higher stiffness and p_c` and $p_c$` can be easily determined from the relatively sharp “kink” in the stress strain curve or the large “drop off” in the stiffness curve.

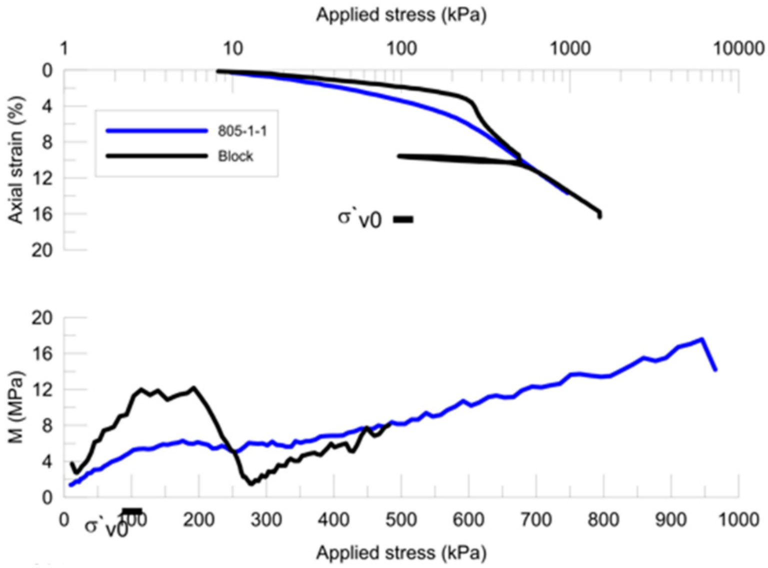


Figure 14: *Oedometr tests on Norwegin soft clay with high quality and poor samplers (M. Long, El Hadj, and Hagberg 2009)*

Therefore if p_c` is of importance in the design calculations it is essential to use as high a quality sampler as possible. In Irish practice this would mean a thin walled (≅ 1.5 mm), 100 mm diameter piston sampler (sometimes known as an ELE sampling tube). A very important consideration is the cutting edge angle and this should be made as sharp as possible. According to (ENISO 2006) this value should not exceed 5°.

PRECONSOLIDATION STRESS FOR CORK ALLUVIUM

Some p_c` values for Cork alluvium are shown in Figure 15. The values were determined using the Casagrande (1936) technique. Various sampler types were used including hand carved blocks from an excavation, ELE samplers with a 30° cutting edge angle and open drive U100 samplers (not now allowed according to ENISO, 2006). Note the zero values mean the preconsolidation stress could not be determined from the test. Despite the samplers not being the best available, the data shows that the alluvium has a p_c` of the order of 20 kPa greater than the in situ vertical effective stress σ'_{v0}. This means an additional 20 kPa approximately can be imposed on the alluvium without significant settlement being experienced. This is consistent with the results of the building monitoring described above.

The SPT N values in the alluvium shown on Figures 4, 7 and 10 also confirm the alluvium is probably of "soft to firm" consistency.

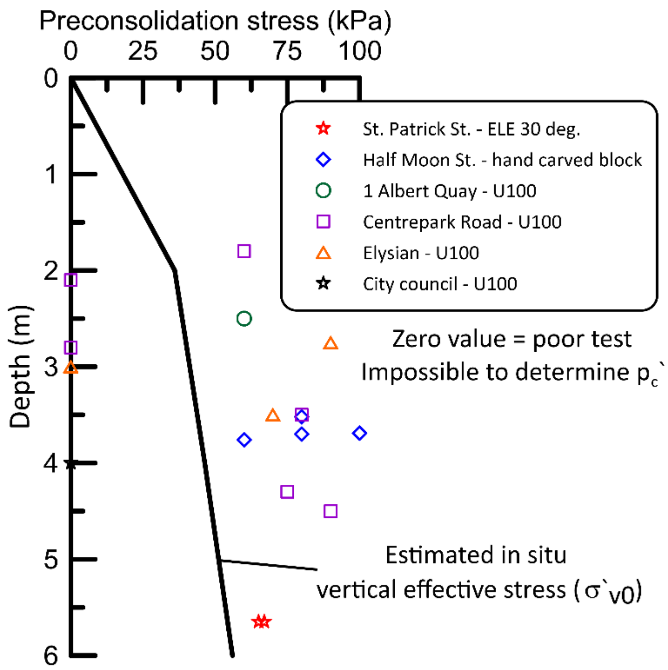


Figure 15: *Some preconsolidation stress (p_c`) values for Cork alluvium compared to the in situ vertical effective stress. Note the zero values mean the preconsolidation stress coould not be determined from the test.*

DUBLIN CASE HISTORIES

COLLEGE STREET HOTEL, COLLEGE ST. (M. Long 2002)

The College St. Hotel (formerly known as the Westin Hotel) at the junction of Westmoreland St and College St. in Central Dublin was developed in a manner where the existing façades were retained, see Figure 16. The existing basement was deepened inside a secant piled wall structure. Ground conditions in the area are typical Dublin conditions with made ground over competent glacial deposits over limestone bedrock.

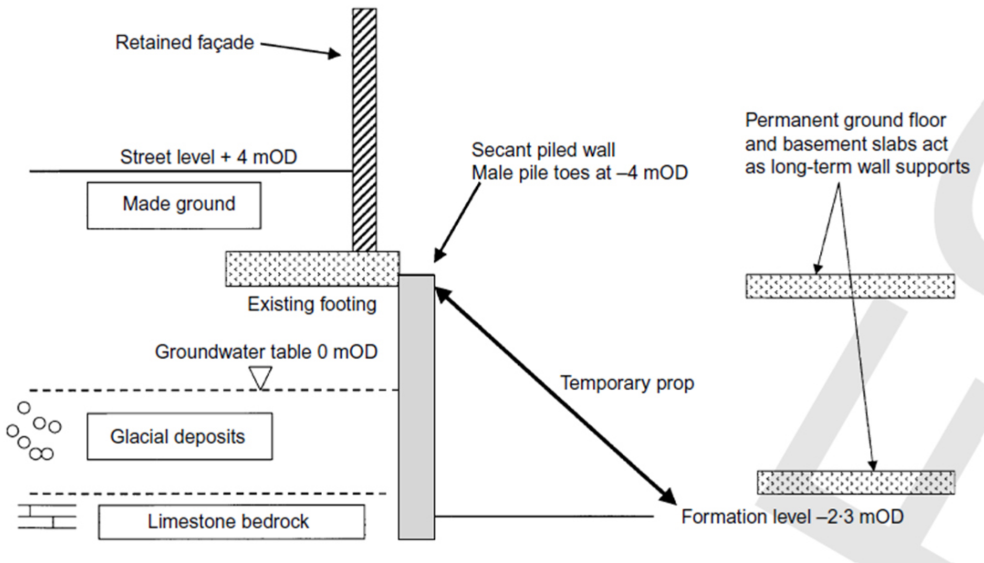


Figure 16: *College Hotel development Dublin – ground conditions (M. Long 2002)*

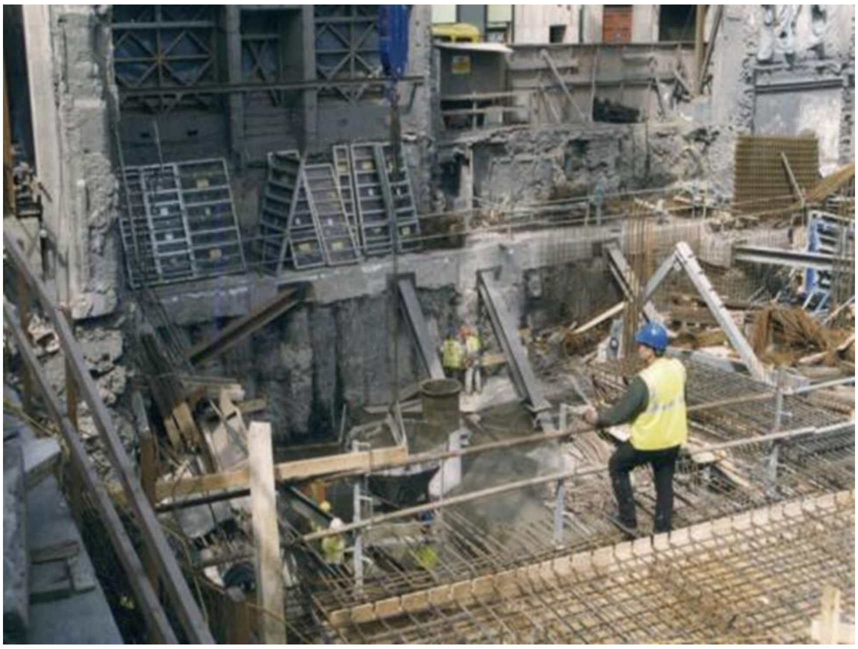


Figure 17: *College Hotel – view of basemnt excavation and retained façades*

A significant concern was the potential settlement of the retained façades (Figure 17) and also some adjacent structures where the foundations were possibly located on made ground.

Unlike the Cork cases the secant piled wall formed an effective cut-off. Significant pumping was carried out both from sump pumps and from a submersible pump in a borehole near the centre of the site. A small decrease in groundwater level during basement works of between 0 m and 0.9 m was recorded. No significant settlements were recorded, see Figure 18.

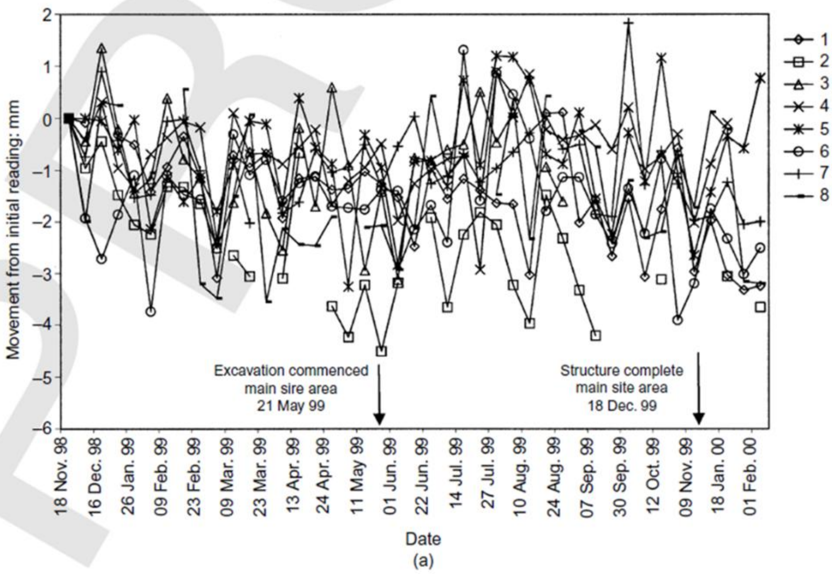


Figure 18: *College Hotel – settlements (M. Long 2002)*

SHAFT WA2 – DUBLIN (PORT) TUNNEL

The Dublin (Port) Tunnel (DPT) provides a link from the motorway system north of Dublin to the port area. A central section of the DPT project comprised twin bored tunnels driven by

Tunnel Boring Machines (TBMs) launched from a central large-diameter shaft, called WA2. The 56.6 m diameter shaft was up to 29 m deep, see Figure 19 (Cabarkapa et al. 2003).

Figure 19: *Shaft WA2 Dublin Tunnel (Photo courtesy Dr. Chris Menkiti, GCG)*

Ground conditions in the area comprised about 31 m of the very competent Dublin Boulder Clay (DBC) over limestone bedrock. The DBC is known to contain lenses of sand and gravel. A very extensive deep well dewatering system consisting of 10 no. 50 m deep wells with submersible pumps was installed. The bedrock was dewatered to facilitate construction.

Given the low permeability of the DBC it could be expected that the development of long-term movements would be very slow, over a period of many years. As described by Menkiti and Long (2015), the Shaft WA2 case history showed the very opposite occurred. Dewatering commenced during a significant pause in construction allowing consolidation settlements, directly linked to pore pressure changes in the clay, to be examined. At the site, lenses of coarse material were present in the DBC. It had been thought that the granular lenses were occluded within the clay till, or inter-connected into a horizontal drainage horizon (Figure 20a).

However, carefully interpreted data demonstrated the existence of a 3-D network of granular zones that were hydraulically interconnected to each other and also to the limestone bedrock (Figure 20b). It seems that the local subglacial drainage system at the time of till deposition was a distributed network of linked cavities or braided canals, which is reflected in the distribution of the granular zones. Groundwater drawdown in the limestone at Shaft WA2 effectively mobilised these connections and resulted in short drainage paths and rapid drainage of the clayey DBC, despite the low permeability of the clayey facies. As can be seen on Figure 21 modest pumping levels resulted in rapid stabilisation of piezometric levels and modest settlements which stabilised after a short time.

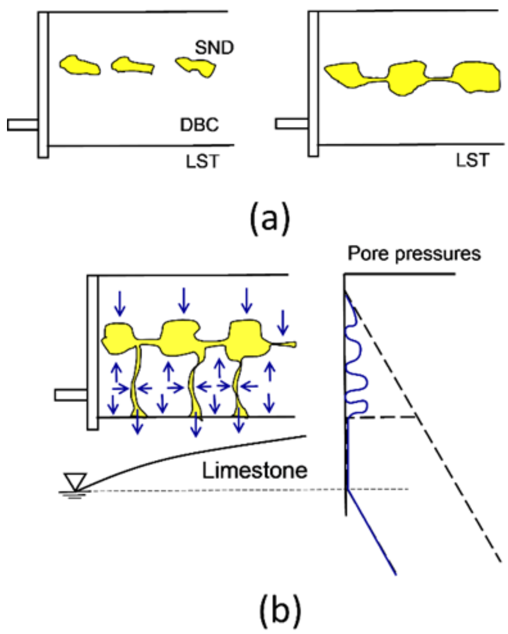


Figure 20: *Ground conditions and pore water pressures at shaft WA2 (Menkiti and Long 2015)*

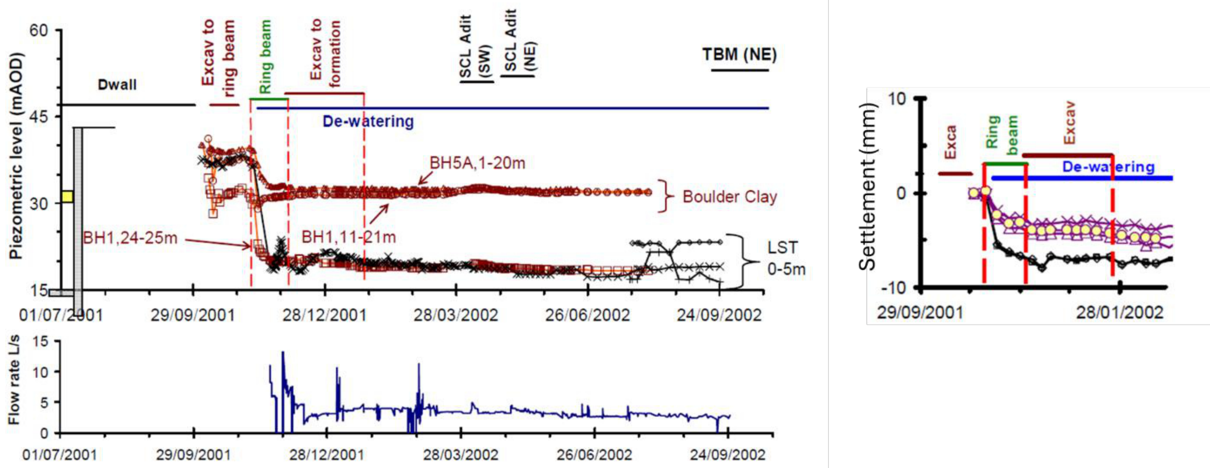


Figure 21: *Piezometric leveLs, ground-water flow and settlment shaft WA2*

It is very important that high quality geotechnical data is available to allow assessments such as these to be made. For the DBC high quality triple – tube coring such as that of the Geobore S systems essential to provide a detailed geotechnical stratigraphy of a particular site and also provide high quality samples for testing.

CONCLUSIONS

The purpose of this paper was to summarise some case histories from Dublin and Cork where consolidation settlements induced by groundwater lowering were of potential concern. Cork and Dublin present contrasting conditions due to the presence of soft alluvium in Central Cork and very competent glacial deposits in Dublin. The work shows:

- At three of the four Cork case histories the settlements measured were very small, probably due to the induced stresses being less than the soil's preconsolidation stress.
- For the fourth Cork case no alluvium was present so settlements were not an issue.
- Recharge wells are a possible remedial measure that could be applied in Cork but clogging of the wells leading to high maintenance requirements is possible.
- There are no well documented case histories of dewatering induced settlement in Dublin.
- The Dublin tunnel case history shows that inter-connected gravel lenses within the Dublin Boulder Clay, can lead to more rapid development of settlement than expected.
- High quality ground investigation including desk studies and good quality sampling is essential for such assessments.

ACKNOWLEDGEMENTS

The author is grateful to many colleagues who collaborated in the work presented. For the Cork case histories valuable input was provided by Martin Murphy of MMOS Consulting Engineers and Toby Roberts of W.J. Groundwater. For the Dublin case histories the author is grateful for the support of Chris Menkiti of GCG and Carl Brangan of ESB.

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EARLY-STAGE IDENTIFICATION, ASSESSMENT, AND MITIGATION OF GROUNDWATER AND GEOTECHNICAL RISKS DURING CONSTRUCTION

James Watson, OGI Groundwater Specialists Ltd

ABSTRACT

This talk presents examples of the approach taken by the authors, in assessing and planning for Groundwater and Geotechnical Risks on three large construction projects in Northern Ireland. The project examples referred to include (i) the planned construction of a 35m deep shaft in close proximity to a live railway, major road, and tidal river (ii) the planned construction of an 80m x 40m tank, excavated to circa 5m bgl, in highly compressible deposits of sleech, and (iii) the planned construction of a Pumping Station Structure, which requires excavation to circa 7m bgl, above an artesian sand aquifer, and in proximity to critical existing infrastructure. The talk presents Groundwater and Geotechnical Risks identified in each case, and details on how these risks were identified and subsequently quantified. In quantifying the identified risks, details of targeted hydrogeological testing and sampling undertaken on each project are presented, which enabled the subsequent calibration of finite element models to real site data. Documentation of designed mitigation approaches to the risks are presented.

Key words: *Geotechnical, risk, construction, mitigation*

ASSESSING GROUNDWATER RISKS FROM LARGE STORMWATER STORAGE TANKS: A CONCEPTUAL SITE MODEL APPROACH

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ABSTRACT

Combined Sewer Overflow (CSO) activations are a way for the sewage undertakers to relieve pressure on the wastewater system when it is overcome during storm deluge events. Some say it is a vital relief system to ensure that the wastewater treatment works are themselves not overcome, or to prevent backing up of stormwater systems into customers properties. Conversely, there is a view that this issue is a function of chronic underfunding or misplaced use of funds by water utility companies when dealing with aging infrastructure. Some of this aged infrastructure has failed to keep pace with the demands of the world. This has resulted in significant pollution of the British waterways. The need for wastewater network investment, specifically reducing the number of activations, is a priority for the public and water utility companies as we start into AMP8 (the eighth regulatory funding cycle for UK water companies). One such investment is stormwater storage in the form of underground tanks. These are designed to attenuate the deluge of stormwater generated during storm events and will contain raw sewage. This paper presents a comprehensive hydrogeological risk assessment methodology for the design of underground stormwater storage, employing a widely accepted industry conceptual site model (CSM) approach. The storage of sewage in stormwater should be in accordance with the Environment Agency's guidelines and Position Statement D regarding the protection of groundwater against pollution. The assessment involves the collection and review of publicly available data, proposed designs, and historical reports to develop a preliminary CSM. This model facilitates the identification of potential contaminant linkages, which can be qualitatively assessed, and the proposed storage tank then assigned a ***RAG*** *(RED, AMBER, GREEN) status based on its perceived risk to the water environment. The findings inform appropriate recommendations and next steps to address any residual concerns.*

INTRODUCTION

The management of Combined Sewer Overflow (CSO) activations is a top priority for water utility companies in the United Kingdom. Growing public and regulatory pressure to reduce these activations has led to significant investments during Asset Management Period 8 (AMP8) aimed at minimising environmental releases. However, the aging wastewater infrastructure struggles to meet increasing demands, and climate change exacerbates extreme weather events, exposing the scale of pollution caused by CSO activations.

To address these challenges, water utility companies are implementing strategies to reduce infiltration and inundation in the sewer network. They are doing this by creating attenuation capacity and enhancing the capacity of wastewater treatment works. Tetra Tech is collaborating with one of the largest UK water utility companies to support these investments. Our hydrogeologists are providing technical expertise on some complex hydrogeological issues associated with such infrastructure projects. A key focus is assessing the potential impact of proposed underground stormwater storage tanks on the water environment. This risk is heightened when the infrastructure is located in proximity to sensitive features such as groundwater source protection zones (SPZs), aquifers, surface water courses, and designated sites.

The Environment Agency (EA) has established guidelines, specifically Position Statement D, which addresses the storage and handling of hazardous substances and is relevant to activities that may pose risks to groundwater. A comprehensive risk assessment is necessary to evaluate the potential impacts of the proposed storage tanks on groundwater and other sensitive receptors.

This paper outlines the principles of groundwater protection as articulated by the EA and provides a framework for assessing the impact of the proposed storage tanks on groundwater receptors.

GROUNDWATER POSITION STATEMENT D

The EA Position Statement D[1] outlines essential guidelines for the protection of groundwater from pollution resulting from the storage and handling of hazardous substances. This statement is applicable to various industrial activities, including:

- Industrial Facilities: Operations involving significant quantities of hazardous materials (such as sewage) must follow strict design and operational standards to prevent groundwater contamination.
- Fuel Retail and Storage: Petrol and diesel filling stations, as well as fuel storage facilities linked to transport infrastructure, are subject to these guidelines.
- Emergency Services and Heavy Machinery: Facilities supporting emergency services or utilizing large machinery, such as those in mining or road haulage, must comply with groundwater protection principles.

Key principles emphasised in the position statement include:

- Design and Maintenance: Facilities must be designed to prevent the release of hazardous substances into the environment, while minimising the input of non-hazardous pollutants to groundwater.
- Engineering Standards: Appropriate engineering practices should be adopted, considering the nature and volume of stored materials and the sensitivity of nearby groundwater.

The EA will typically oppose developments deemed to pose an unacceptable risk to groundwater. For new facilities where above-ground storage is impractical, additional guidance on underground storage options is provided.

Overall, EA Position Statement D serves as a critical framework for ensuring that developments involving hazardous substances prioritise groundwater protection, thereby promoting sustainable environmental practices and safeguarding public health.

Tetra Tech has considered this guidance and has applied it to the storage of sewage in underground stormwater tanks.

METHODOLOGY

The risk assessment for underground storage follows a widely accepted industry approach, beginning with an initial desktop study (DTS) to identify viable source-pathway-receptor (SPR) relationships (contaminant linkages), and to evaluate their likelihood and significance.

The DTS generally involves collecting and reviewing publicly available data, proposed designs, and historical reports from water utility companies to develop a preliminary conceptual site model (CSM). This model helps identify potential contaminant linkages,

[1] https://assets.publishing.service.gov.uk/media/5ab38864e5274a3dc898e29b/Envirnment-Agency-approach-to-groundwater-protection.pdf

which are then qualitatively assessed, and the stormwater storage location assigned a **RAG** (*RED, AMBER, GREEN*) status based on its perceived risk to the water environment. Based on the RAG status, appropriate recommendations and next steps are then proposed by the hydrogeologist to address any residual concerns.

CONCEPTUAL SITE MODEL – WORKED EXAMPLE

To provide context to the approach a Tetra Tech worked example for one of the larger UK water utility companies is presented below.

SOURCE

The source of concern was straightforward: sewage. However, the proposed quantity of sewage, along with the corresponding storage capacity and dimensions of the tank, was determined through hydraulic modeling of the wastewater network. This modeling provided essential context for understanding the perceived risks to the water environment.

Another critical factor was the proposed location of the storage tank. Water utility companies often face constraints at the time of site selection, aiming to minimise costs by using existing land holdings and leveraging the hydraulic advantages of proximity to the CSO and wastewater network. This approach reduces the need for acquiring or leasing new land and avoids additional investment in terms of hydraulic improvements. These locations can be often situated in environmentally sensitive areas.

For this case study site, the proposed storage tank was planned for construction on a parcel of land adjacent to the existing CSO. This tank was designed to accommodate up to 1,000 m^3 of sewage and to extend as deep as 8 metres below ground level (m bgl).

PATHWAYS

This aspect of the CSM was one of the most crucial but also the one with the greatest uncertainty, requiring professional judgment to fill knowledge and data gaps. To understand the potential pathways, a review of hydrological, geological, and hydrogeological data was conducted. An overview of each environment is presented below.

Hydrology

A named brook flowed adjacent to the proposed storage location and confluenced with a major river approximately 6.5 km downstream. The brook appeared to flow within a naturalised channel with minimal culverting. Other brooks and watercourses confluenced with it before discharging into the major river. The depth of the riverbed relative to the local ground surface was not known.

The brook flowed through a local nature reserve, an ancient woodland, and a Site of Special Scientific Interest (SSSI), approximately 3 km north of the site.

Geology

The review was divided into two primary scales: the regional geological context and the more localised geological conditions. At the regional scale, the proposed storage location was situated on a narrow band of Head deposits that aligned with the course of the nearby brook. According to the British Geological Society (BGS), these Head deposits were characterised by a mixture of clay, silt, sand, and gravel.

Surrounding this thin band of Head deposits, the superficial geology consisted of Till deposits, described as clayey, sandy, gravelly, and cobbly. The superficial deposits proximal to the proposed storage are illustrated in Figure 1.

Figure 1: *Superficial Deposits*

Underlying the superficial deposits was the sandstone bedrock of the Chester Formation, part of the Sherwood Sandstone Group parent unit.

BGS borehole records proximal to the proposed storage location were accessed and evaluated to identify local geological conditions. The results of this exercise are presented in Table 1 below.

Borehole ID	Total Depth (m bgl)	General Ground Conditions (m bgl)
1	9.00	0.00 to 2.90 – Boulder Clay* 2.09 to 9.00 – Weathered Sandstone
2	21.00	0.00 to 5.40 – Made Ground 5.39 to 10.90 – Sand/Sandy Clay 10.90 to 21.00 – Weathered Sandstone
3	13.20	0.00 to 4.70 – Made Ground 4.70 to 12.75 – Clayey Sand/Sand/Sandy Clay 12.75 to 13.20 – Weathered Sandstone
4	11.30	0.00 to 4.20 – Silt Sand 4.20 to 11.30 - Weathered Sandstone
5	10.60	0.00 to 1.10 – Sandy Clay with gravels 1.10 – 10.60 – Weathered Sandstone
6	22.48	0.00 to 21.00 - Boulder Clay* 21.00 to 22.48 – Bunter Pebble Beds**
7	112.78	0.00 to 38.71 – Sand Clay/Sand and Gravels 38.71 – 50.90 – Red quicksand 50.90 to 112.78 – Bunter Pebble Beds*
8	304.80	0.00 to 22.56 – Mainly Clay with sands and "stones" 22.56 to 37.19 – Mainly Sands with occasional gravel observations 37.19 to 304.80 - Sandstone

m bgl – metres below ground level
*Boulder Clay – Obsolete name for Till deposits
**Bunter Pebble Beds – Obsolete name for the Chester Formation

Table 1: *Local Geological Conditions based on BGS records locally*

Hydrogeology

The hydrogeological review, like the geological one, was conducted with both regional and local perspectives in mind. A review of publicly available mapping services revealed that the proposed storage location was situated within Source Protection Zone 2 (SPZ) of an abstraction borehole, as illustrated in Figure 2. An examination of the borehole records for the abstraction borehole (referenced by Borehole ID no. 8 in Table 1) indicated that the borehole targeted the Chester Formation.

Figure 2: *Porpsoed Storage Location in Relation to SPZs*

At the local scale, the BGS borehole records were re-evaluated to identify groundwater level observations, strikes, and monitoring results from hydrogeological testing, thereby enhancing the understanding of the hydrogeological conditions in the area. Only two boreholes recorded groundwater level observations. The first was a shallow superficial borehole (10.67m deep), where groundwater was detected at the end of drilling, approximately 4 metres below ground level (m bgl). The second observation was made at the abstraction borehole, where groundwater levels were measured between 38.10 and 39.62 m bgl, near the interface between the superficial and bedrock geology.

To further assess contemporary groundwater levels in the Chester Formation, data from nearby Environment Agency (EA) observation monitoring boreholes were analysed, as current groundwater levels were not well understood. Since the 1980s, groundwater levels in these proximal boreholes had shown an increase of between 5 and 9 metres. The time-series datasets for three nearby observational boreholes are illustrated in Chart 1.

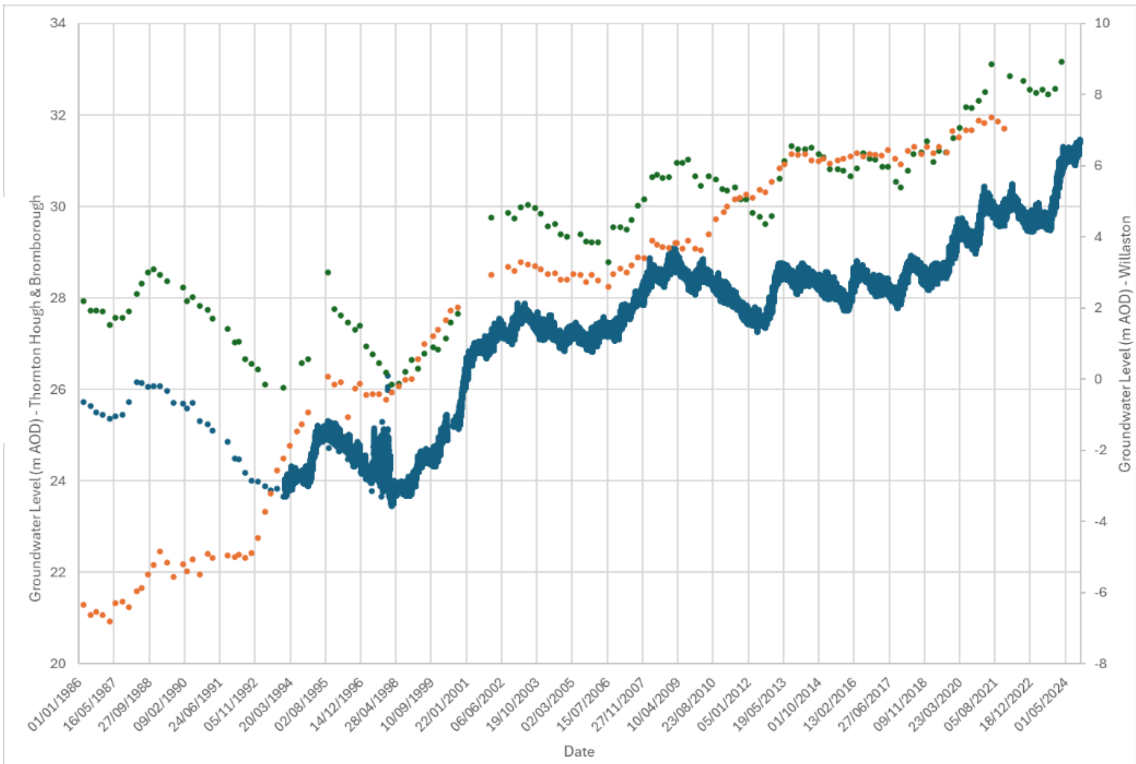

Chart 1: *Groudnwater Levels in Proximal EA Observational Boreholes*

PRELIMARY CONCEPTUAL SITE MODEL

The preliminary CSM was constructed based on the publicly available data and there was no site-specific environmental data to define the ground conditions more accurately. Therefore, there has been interpolation of ground conditions based on the data reviewed.

Geology and Hydrogeology

The interpreted geology and hydrogeology could be categorised into four main layers:

- Layer 1a – A layer comprising of predominately clay with localised bands of more gravelly or sandy deposits. Where present the sand could be very compacted and described as weathered sandstone. The thickness spatially varies; therefore, it is considered the protection afforded by this layer to the underlying aquifer may vary spatially. If groundwater is encountered, it is likely to be discrete and localised within more permeable sandy or gravelly horizons, rather than representing a continuous body of water.
- Layer 1b – An unproven thickness of Head deposits. This layer appears to align with the adjacent brook. Its composition and thickness is unknown locally (it has been assumed to be 3m for the purpose of this CSM), therefore the protection afforded by it to underlying groundwater is unknown. Given that the Head deposits are classified as a secondary 'B' aquifer, groundwater could potentially be present. However, there is insufficient evidence to definitively indicate either the presence or absence of groundwater in this layer.
- Layer 2 – Weathered Sandstone, it could be up to c.12m thick.
- Layer 3 – Chester Formation, a red sandstone from 21m bgl, but on average from c.36m bgl.

Based on the EA observation boreholes the Chester Formation was encountered at much shallower depths with thinner overlying clay deposits.

For Layers 2 and 3 the groundwater conditions are as follows. Regionally, the Chester Formation functions as an unconfined aquifer, with groundwater levels fluctuating within the aquifer body. Limited low-permeability superficial deposits may act as confining layers. Near the proposed storage tank location, a relatively thicker layer of clay rich superficial deposits, could provide additional protection and serve as a confining layer, as discussed further below.

Groundwater flow generally trends in an easterly direction. By extrapolating groundwater elevations from the EA observation boreholes using a derived hydraulic gradient, it is estimated that groundwater near the proposed storage tank location could be approximately 10m bgl. Given that there were typically no groundwater strikes or observations in boreholes targeting Layers 1a, 1b, or 2, it is likely that groundwater from Layer 3 has risen into Layer 2. However, where it intersects with Layer 1a, the clay rich deposits may act as a confining layer, providing a degree of protection.

Hydrology

It is considered likely that the brook has a natural channel within the locality the proposed storage tank. The brook flows into a sensitive receptor (SSSI) c.3 km north of the site. There are several accretions prior to entering the brook entering the SSSI, however the significance of them is not currently understood.

The depth of the riverbed is not known; therefore, it is not possible to determine if there is connectivity with underlying groundwater. There is insufficient evidence to rule out the absence or presence of groundwater in Layer 1b, however, given it is designated a secondary 'B' aquifer this hydraulic connectivity cannot be ruled out.

Contaminant Linkages

Based on the preliminary CSM it was determined that there could be 3no. contaminant linkages. These are detailed in Table 2 below:

Contaminant Linkage	Source	Pathway	Receptor
1.	Storage Tank	• Through limited unsaturated zone to underlying groundwater • Through groundwater in the Chester Formation towards the abstraction borehole	Abstraction Borehole
2.		• Through limited unsaturated zone to underlying groundwater	Principal Aquifer – Chester Formation
3.		• Lateral migration to the adjacent potentially groundwater bearing Head deposits • Migration into the brook • Flow into the SSSI	SSSI

Table 2: *Contaminant Linkages*

It is acknowledged that there is limited site-specific data and the preliminary CSM and resulting contaminant linkages were based on publicly available data. However, there is insufficient evidence to suggest that the findings are not valid, therefore the proposed storage tank has been assigned a **RED** RAG score. This means that it is determined to pose a **high risk** to the water environment. based on the EA's Groundwater Protection Position Statement 'D' and it is considered likely the EA would object the proposed development.

Preliminary CSM

A north to south 2-D cross-sectional view of the ground conditions is presented in Figure 3 below.

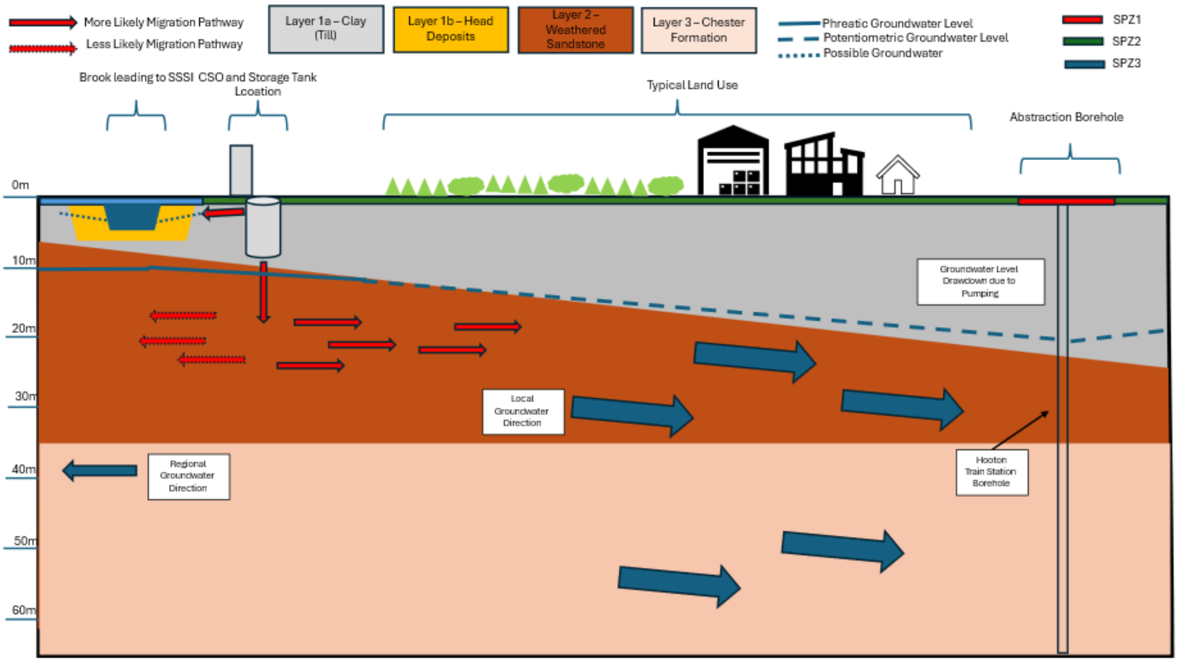

***Figure 3:** Preliminary CSM*

RECOMMENDATIONS

The preliminary conceptual site model (CSM) and contaminant linkages were developed using non-site-specific data. To address these data gaps, the following actions were recommended:

- Intrusive Investigation: Conduct investigations to confirm geological and hydrogeological conditions and installation of monitoring boreholes.
- Groundwater Monitoring: Implement a subsequent programme of groundwater level and quality monitoring of the newly installed boreholes.
- Walkover Survey: Conduct a walkover of the brook from the storage tank location to its confluence with the SSSI to assess riverbed and channel conditions, as well as to visually evaluate flow and accretions.

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Relevant information on the natural environment accessed through the following website: https://magic.defra.gov.uk/magicmap.aspx

Relevant information on the geological environment accessed through the following website: https://geologyviewer.bgs.ac.uk/?_ga=2.251521731.434233611.1731428017-1846064384.1731428017

Relevant borehole logs accessed through the following website: https://www.bgs.ac.uk/map-viewers/geoindex-onshore/

Relevant information on the EA regional groundwater monitoring network accessed through the following website: https://environment.data.gov.uk/hydrology/landing

SESSION III

GROUNDWATER ENGINEERING FOR HYDROGEOLOGISTS AND GEOTECHNOLOGISTS

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ABSTRACT

In the construction industry, the presence of groundwater, particularly challenging when high water pressure is encountered, often complicates safe work during ground excavations. These challenges arises when designers do not fully understand the detrimental impact of groundwater. Hydrogeologists are frequently engaged to diagnose and develop solutions, but expertise in groundwater does not always extend to the complexities of soil mechanics and geotechnical engineering often encountered.

Groundwater engineering links hydrogeology and soil mechanics, as demonstrated by phenomena like ground heave, soil piping, and soil liquefaction. Ground heave occurs when pore water pressure exceeds the weight of overlying soil, causing the ground to lift and potentially fail. Piping happens when groundwater forces out loose material, creating a void that deepens into a channel, allowing water to flow to the surface, potentially leading to washout. Soil liquefaction, where high pore-water pressure reduces effective stress, and ultimately strength, can cause ground failure, especially in earth slopes, and can be exacerbated by machinery vibrations. Tidal loading on coastal aquifers can also create high pore-water pressure, impacting on the design of earth retaining structures. Assuming that low-permeable clay layer will prevent water transmission, from a tidal water body can lead to ground excavation failures. Additionally, Darcy's law, when applied to deforming soils, requires consideration of the relative velocities between groundwater and soil particles, which is critical for accurate pore-pressure and soil deformation predictions. Soil shear strength, fundamentally dependent on the principle of effective stress, and pore water pressure, is a key factor in requiring groundwater control.

Keywords: *groundwater engineering, hazards, heave, piping, liquefaction, tidal loading*.

INTRODUCTION

Groundwater regularly provides challenges to the construction industry during excavations below the water table in unconfined ground conditions and below the potentiometric surface in a confined artesian aquifer, should the excavation formation become close to the aquifer. To mitigate the impact of groundwater on construction, various solutions can be implemented in advance, requiring expertise in civil engineering, hydrogeology, and geotechnology. However, due to the multidisciplinary nature of this field, these areas are rarely integrated into a single educational program. Note that geotechnology is used to incorporate those with not just geotechnical engineering, but also the knowledge, skill and practical experience in both civil and mechanical engineering. The term used in this paper to encompass the above skills, and often used by others, is "Groundwater Engineering," with the author describing himself as a "Groundwater Engineer." In the experience of the author, it is very rare that an individual has expertise in all the above subjects, and this is the reason that a balanced project design team is recommended. However, without the luxury of a team, it often comes down to a single individual to straddle the above knowledge, to complete a groundwater engineering design. To assist the groundwater engineer with identifying the hazards to a construction project from groundwater, together with quantifying and then mitigating the hazard, the following sections are aimed at providing some guidance and direction. Groundwater hazards described in this paper relate to those encountered when constructing excavations within the hydrogeological environment, as described in Figure 1. These hazards include inundation by water (flooding), ground settlement (subsidence), structural uplift, ground heave, piping, liquefaction, slope instability, and tidal loading. In addition, the paper concludes by identifying where traditional analytical techniques need to be enhanced to accommodate the particular phenomena associated with combining the theory used within hydrogeology and geotechnical engineering.

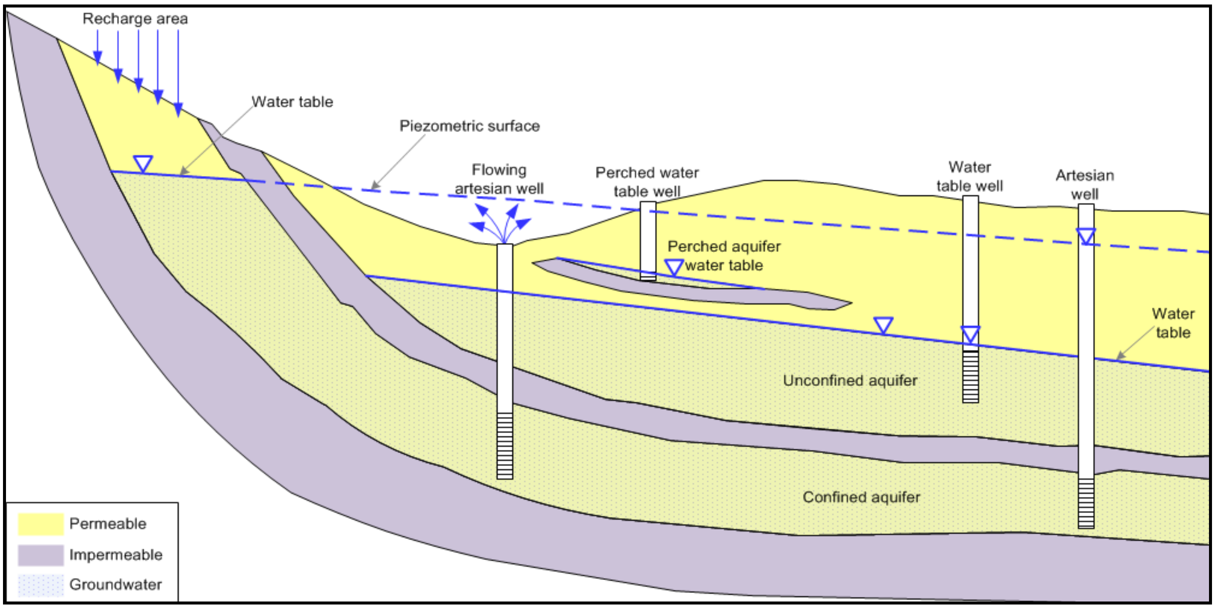
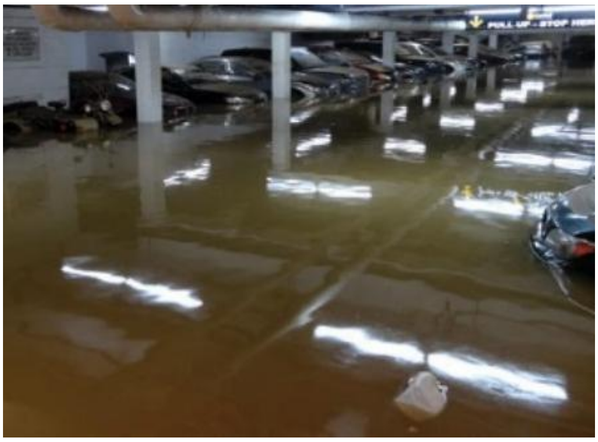


Figure 1. *Depiction of a typical hydrogeological aquifer system.*

Groundwater Inundation

The hazard caused by the inundation of excavation by groundwater (Figures 2 & 3) is the most widely understood, and is often the most straightforward to mitigate in practice. If the ground has sufficient strength, such as fractured rock or clean gravel, sump pumping is the most commonly used technique for abstracting inflowing groundwater.



Figures 2 & 3. *A construction site and parking basement with inundation from groundwater*

Sump pumping

Utilising sump pumping (Figures 4 & 5) in isolation is regularly used in the construction industry, particularly when excavating in fractured rock, and stable granular sand & gravels. However, there are several destabilising phenomena that must be considered when designing a groundwater management system. Without consideration, such phenomena create hazards that can be detrimental to a project, including human health & safety.

Moreover, relying solely on sump pumping does not guarantee a sufficient reduction in pore water below ground level. As a consequence, loose soil, such as silty sand, can remain in an extremely unstable state, and unsuitable for a safe and stable working environment.

Figures 4 & 5. *Traditional sump pumping from shafts*

<u>Loss of ground strength of the working formation</u>

When working below water table, with inflowing groundwater abstracted by sump pumping, the pore-water pressure immediately below the excavation formation will be higher than under hydrostatic conditions. Based on the principle of effective stress, this will result in a low effective stress, and consequently a low shear strength. In loose ground such as fine sand or silts, the ground will remain in an unworkable unstable condition, resulting in delays and working hazards. Simple groundwater control techniques to reduce the pore-water pressure, such as well-pointing or suction wells, can have a dramatic positive effect on the site. Figures 6 & 7 present the same site (i) before and (ii) after a wellpointing operation.

Figures 6 & 7. *Sump pumping of groundwater versus using a wellpointing operation*

<u>Abstraction and discharge of silts</u>

When pumping from a sump pump, it is good practice to filter the groundwater before abstracting the water with a pump. Without such filtration, the water collected has a high degree of silt content. This collected groundwater will then, at considerable expense, need to be treated using equipment such as a "Siltbuster" prior to discharge to a local water course.

The continuous abstraction of silts means that the silt particles must originate from the ground at some point. Therefore, over the duration of sump pumping, the volume of silt removed from the ground, known as "*ground loss*", can become substantial, and create a hazardous reduction in ground strength, even outside the safety barriers of an excavation caused by the silts being transported by the groundwater flow. This area outside the safety barriers is often considered safe as it is not within the excavation. However, ground lost from below, results in a major hazard to the project and to personnel. This loss of ground can be mitigated using a suitable groundwater control operation, such as wellpointing, suction wells, or wells using electro-submersible pumps. These operations result in groundwater being abstracted via wells or wellpoints, designed to only remove clear water, with silts remaining in the ground. Figures 8 & 9 depict typical quality of discharge water from sump pumps versus wellpoints.


Figures 8 & 9. *Discharge of water from sump pumping versus discharge from wellpointing*

Changes effective resulting from the lowering of the water-table

Lowering the water-table takes place as a result of the abstraction of groundwater below the initial water-table. Abstracting groundwater results in a reduction in the pore-water pressure immediately surrounding the well, or wellpoint. This results in a difference in head between that at the water-table, and that surrounding the wellpoint. This results in a downward direction of groundwater flow, and the water-table will fall as pore-water pressure reduces.

A fundamental equation of soil mechanics is the Principle of Effective Stress (Terzaghi, 1922)

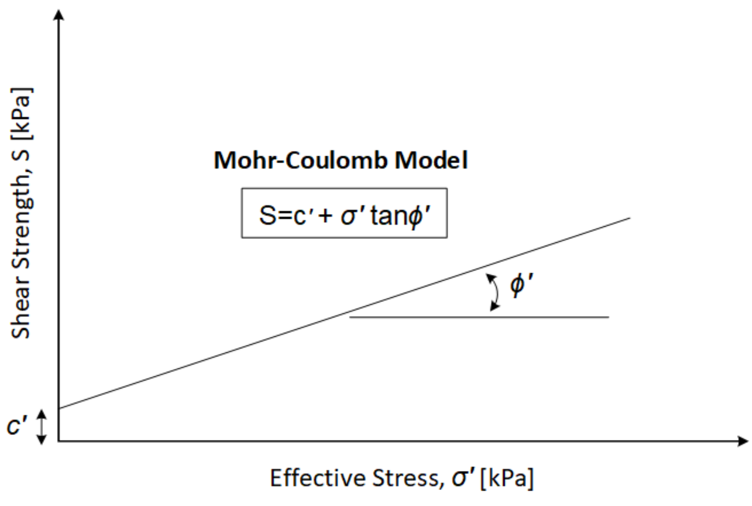
$$\sigma' = \sigma^T - u_W \tag{1}$$

where σ' is the effective stress, (i.e. the interparticle stress between soil grains), σ^T is the total stress within the soil mass and u_W is the pore-water pressure within the saturated voids.

This fundamental equation demonstrates that when there is a unit reduction in pore-water pressure, then for an unchanging total stress, the effective stress increases by the same unit of stress. Equally, when the total stress is reduced on soil, such as when soil is excavated, and the pore-water pressure remains constant, the effective stress will reduce.

Increase in soil shear strength resulting from the lowering of the water-table

A second phenomenon occurs in particulate soil when there is an increase in effective stress. This phenomenon results in an increase in interparticle effective stress caused by a greater frictional resistance to shear stress, and the soil shear strength increases.



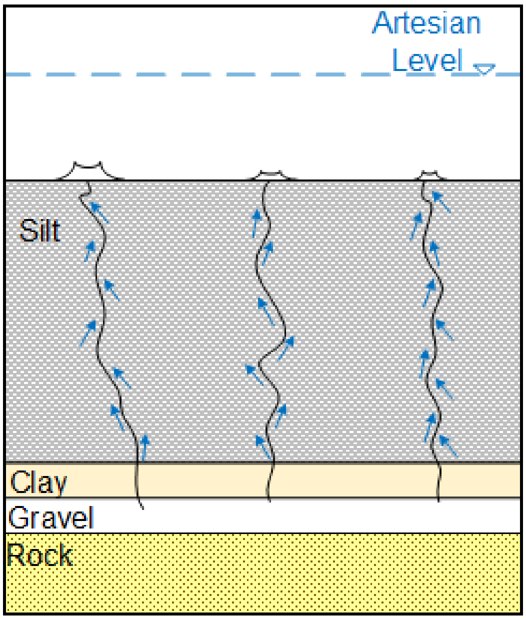
Unlike the single equation for the principle of effective stress (1), there are many models that relate the shear strength to the effective stress. One such model is the Mohr-Coulomb model (Figure 10), where there is a linear relationship between the shear strength and the tangent of the angle of internal friction (ϕ'). Note that there is a residual shear strength, referred to as the cohesive strength (c'), even when the effective stress (σ') is zero.

Figure 10. *Mohr-Coulomb Model (Pietruszczak, S. (2010), after Coulomb, 1776)*

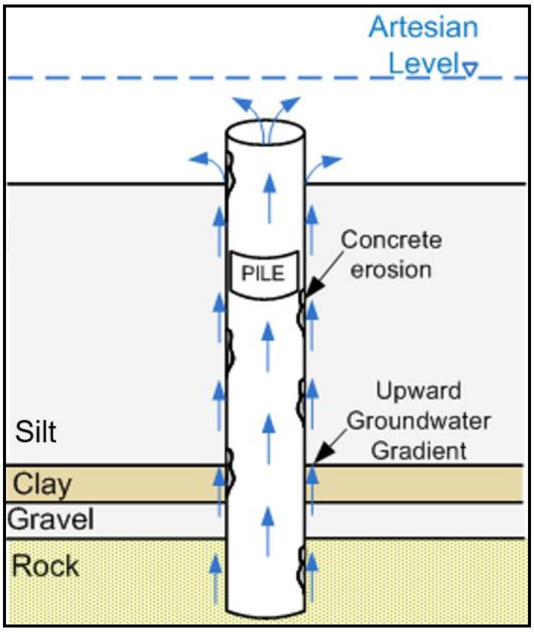
Soil piping from groundwater ingress

When excavation reaches a depth where the artesian groundwater piezometric head in a deeper confined aquifer is above the excavation level (regardless of whether the piezometric head is above the original ground level), groundwater is forced upward through the soil.

Often the soil has enough cohesion to prevent significant groundwater from flowing upwards under such force. However, if there are natural pathways through the ground (Figure 11 & Figure 12), or a manmade structure has created a pathway, the groundwater will see this as a preferential migration pathway, and travel up through these pathways, carrying silts which will provide further ground loss.



Figures 11 & 12. *Upward migration of groundwater through natural pathways*



Figures 13 & 14. S*eepage alongside a curing concrete pile from an artesian stratum.*

An example of a preferential pathway is alongside a curing concrete pile (Figures 13 & 14). This has the potential of both eroding the wet concrete before it has cured, together with mobilising the soil surrounding the pile, so impacting on the performance of the pile, such as the loss of frictional capacity for friction piles.

Soil batter instability

Excavations are often constructed within "open batters." This means that there is no additional support other than through the strength of the soil itself. If there is a high water-table within the soil slopes of the excavation, the shear stress can exceed the shear strength, and the slope will likely fail. Again, groundwater control can contribute to mitigation of the slope failure of weak soils. Lowering of the pore-water pressure increases the effective stress within the soil, resulting in the increase in shear strength, so stabilising the excavation batter.
Figures 15 illustrates the shear failure of a soil slope resulting from progressive failure of a particularly unconsolidated layer at toe level. A combination of deep vacuum suction wells, augmented by the construction of compacted passive angular stone drains, resulted in the stabilisation of a steep soil batter at a 45^{o} slope angle as depicted in Figure 16.

Figure 15. *Progressive slope failure caused by a saturated soil layer at the toe*

Figure 16. *Construction of stable slopes with vacuum wells & passive angular stone drains*

Hazards from artesian pressure in underlying confined artesian aquifers

Hazards can arise when an excavation progresses through low-permeability materials to a level near the top of a confined aquifer under artesian conditions. Artesian conditions occur when the groundwater pressure within the confined aquifer is higher than atmospheric pressure at the top of the aquifer. This results in the piezometric surface being above the top of the aquifer, though not necessarily above ground level. Two potential hazards associated with artesian pressure are (i) structural uplift and (ii) basal ground heave.

(i) Structural uplift

During excavation through low-permeability, structurally competent ground such as stiff clay, the presence of an underlying confined aquifer under artesian conditions where the piezometric head is above the excavation level can create a hydraulic gradient. This gradient forces groundwater to flow upwards from the confined aquifer into the excavation. The rate of water ingress through the low permeable soil to the excavation is often very low, and it is easy not to distinguish this groundwater ingress from water collected from rainfall.

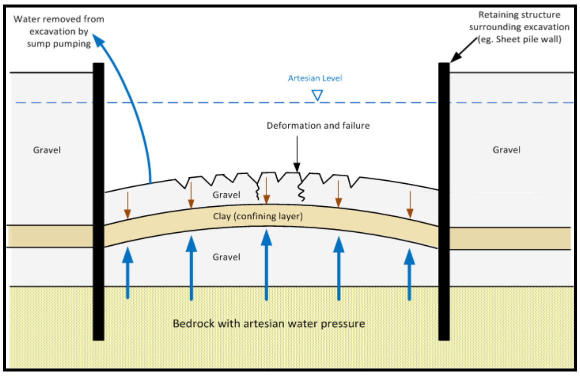
However, if a concrete slab is poured over the full excavation, which is regularly performed, the uncured slab becomes effectively impermeable. As a consequence, even with the low ingress of groundwater seeping through the clay, water pressure builds up between the clay and concrete. As this water pressure increases, it can rise higher than the weight of the concrete slab, and uplift of the slab will occur. It is noted that this ingress will continue until there is a balance between the water pressure beneath the slab, and the weight, or stress resistance of the slab. With there being an effectively infinite source of groundwater in the underlying aquifer, this balance can occur with either (i) the slab lifting until there is a reduced water pressure head over the slab or (ii) the water pressure cracks or penetrates the uncured concrete, so creating a flow path through the slab, reducing the water pressure beneath the slab to hydrostatic conditions (Figures 17 & 18).

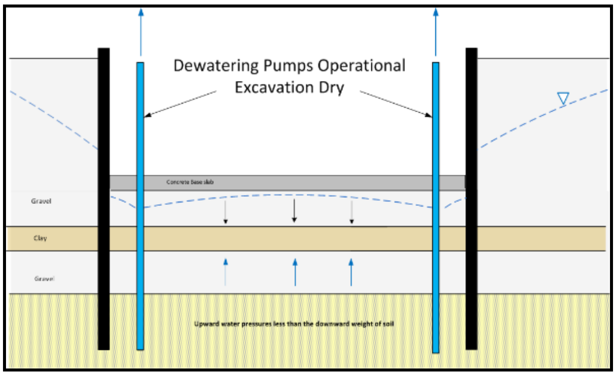

Figures 17 & 18. *Examples of structural uplift, including cracking of a concrete slab.*

If recognised in advance, a structural engineer can design very simple solutions to mitigate this hazard. This can be achieved by constructing a permeable drainage layer beneath the slab, combined with a number of pressure relief points within the slab, which can then be plugged and grouted after the curing of the concrete slab.

(ii) Basal ground heave

A similar phenomenon can occur when an artesian aquifer exists below a low permeable confining stratum, which has sufficient artesian water pressure to lift the entire ground mass.





Figures 19 & 20. *Ground heave caused by artesian pressure and mitigation using wells*

Mitigation of ground heave can be achieved by installing vertical wells (Figures 19 & 20) in advance of excavation. These wells can be actively pumped to reduce the artesian head in a confined aquifer, or if the clay is competent, using a passive system of pressure relief wells.

Soil liquefaction

Soil liquefaction occurs when the pore water pressure in the soil voids is greater than the total stress, resulting in a negative effective stress, and subsequently an extremely low soil shear strength. This can lead to ground failure, especially for earth slopes. Liquefaction is especially exacerbated by ground vibration caused by machinery, turbines and earthquakes.


Figures 21 & 22. *Wind turbines produce soil vibration and an example of liquified soil*

Soil settlement as a consequence of groundwater control

A successful groundwater control operation mitigates groundwater flooding, prevents basal heave and structural uplift, together with the stabilization of the ground by increasing the shear strength. Clearly, this has many positive attributes. However, increasing the effective stress also has another impact, which is the reduction in the void ratio of the soil structure. Excessive increase in effective stress, particularly above the pre-consolidation pressure, can result in the volumetric reduction and so the consolidation of the soil, which can produce surface ground settlement, as well as other potential soil movements.

Tidal loading on a confined aquifer

When a water body subject to tidal behaviour overlies a low permeable clay layer, it is often specified that the boundary condition is the average sea level, as there is very little flow through the impermeable layer within a tidal cycle of 745 minutes. However, as the rising tide provides a weight loading on the seabed, this transmits to an increase of total stress on the underlying permeable saturated sand stratum. This increase in total stress results in a significant rise in pore-water pressure, which in turn migrates towards the land. Such an increase in the pore-water pressure results in a significant uplift on buried structures including underpasses, subways and shafts. This can cause structural uplift and ground heave, together with groundwater piping and ground instability during excavation construction.

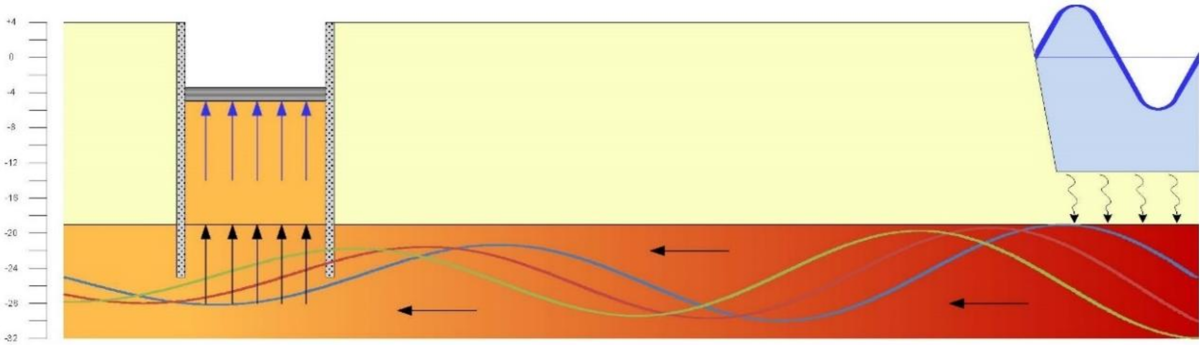


Figure 23. *Tidal loading on a low permeability seabed causing an increase in pore pressure*

Revisiting familiar hydrogeological concepts

This next section revisits a number of familiar hydrogeological concepts, from the perspective of geotechnical engineering. This includes Darcy Velocity (Figure 24), Darcy's Law and the Dupuit-Forchheimer simplification for groundwater flow in unconfined phreatic conditions.

Darcy Velocity

Darcy velocity, Q_w [L/T] is the flow rate, Q_w [L^3/T] of a fluid (normally water) across a cross-section of area, A [L^2] within a porous medium. This can be written as:

$$W = Q_w/A \tag{2}$$

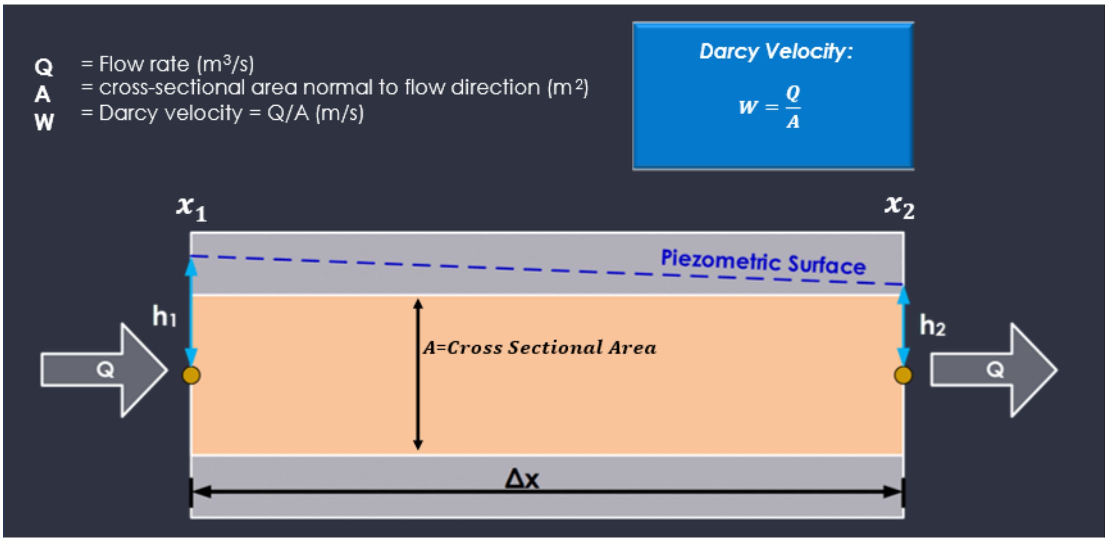


Figure 24. *A depiction of Darcy velocity*

For a fractured rock, or a well-consolidated incompressible granular soil, such as a coarse sand or gravel, Darcy Velocity is the average flow rate moving over a unit sectional area.

In the x-dimension, the Darcy velocity, W_x can be derived from Darcy's Law as follows:

$$W_x = -k_x \frac{\partial h_w}{\partial x} \tag{3}$$

where k_x is the coefficient of permeability in the x-direction and h_w is the hydraulic head. Applying continuity principles under transient conditions, results in equation (4).

$$\frac{\partial}{\partial z}[W_x] + \frac{n_w}{\rho_w}\frac{\partial \rho_w}{\partial t} + \frac{\partial n_w}{\partial t} = 0 \tag{4}$$

where n_w is the effective porosity, and ρ_w is the mass density of water. Substituting Darcy's Law then yields.

$$\frac{\partial}{\partial x}\left[-k_x \frac{\partial h_w}{\partial x}\right] + \frac{n_w}{\rho_w}\frac{\partial \rho_w}{\partial t} + \frac{\partial n_w}{\partial t} = 0 \tag{5}$$

Substituting

$$\frac{n_w}{\rho_w}\frac{\partial \rho_w}{\partial t} = n_w c_w \gamma_w \frac{\partial h_w}{\partial t} \tag{6}$$

where c_w is the volumetric compressibility of water, with γ_w the water weight density, and

$$\frac{\partial n_w}{\partial t} = c_s \gamma_w \frac{\partial h_w}{\partial t} \tag{7}$$

where c_s is the volumetric compressibility of the soil matrix, so yielding

$$\frac{\partial}{\partial x}\left[k_x \frac{\partial h_w}{\partial x}\right] = \gamma_w (c_s + n_w c_w) \frac{\partial h_w}{\partial t} \tag{8}$$

otherwise written as

$$\frac{\partial}{\partial z}\left[k_x \frac{\partial h_w}{\partial x}\right] = S_s \frac{\partial h_w}{\partial t} \tag{9}$$

where S_s is known as specific storage. For a confined aquifer of saturated thickness, b, this equation can be written

$$\frac{\partial}{\partial z}\left[b k_x \frac{\partial h_w}{\partial x}\right] = b S_s \frac{\partial h_w}{\partial t} \tag{10}$$

For an unconfined aquifer with a phreatic surface, there is an additional right hand transient coefficient known as specific yield, S_y

$$\frac{\partial}{\partial x}\left[b k_x \frac{\partial h_w}{\partial x}\right] = (b S_s + S_y) \frac{\partial h_w}{\partial t} \tag{11}$$

These storage terms can then be combined into a Storage Coefficient, or Storativity, S

$$\frac{\partial}{\partial x}\left[b k_x \frac{\partial h_w}{\partial x}\right] = S \frac{\partial h_w}{\partial t} \tag{12}$$

For steady-state, non-leaky aquitard conditions, with Transmissivity, $T = b k_x$, this equation can be simplified as

$$\frac{\partial}{\partial x}\left[b k_x \frac{\partial h_w}{\partial x}\right] = \frac{\partial}{\partial x}\left[T \frac{\partial h_w}{\partial x}\right] = 0 \tag{13}$$

and under radial conditions

$$\frac{\partial}{\partial r}\left[r b k_r \frac{\partial h_w}{\partial r}\right] = \frac{\partial}{\partial r}\left[r T \frac{\partial h_w}{\partial r}\right] = 0 \tag{14}$$

Thiem (1906) published a solution to the above steady-state radial flow equation, for the pumping at a rate of Q_w from a well with radius r_w. This results in a steady state constant head, h_w, at the well, with a fixed head h_o, specified at a radius of influence, R_o.

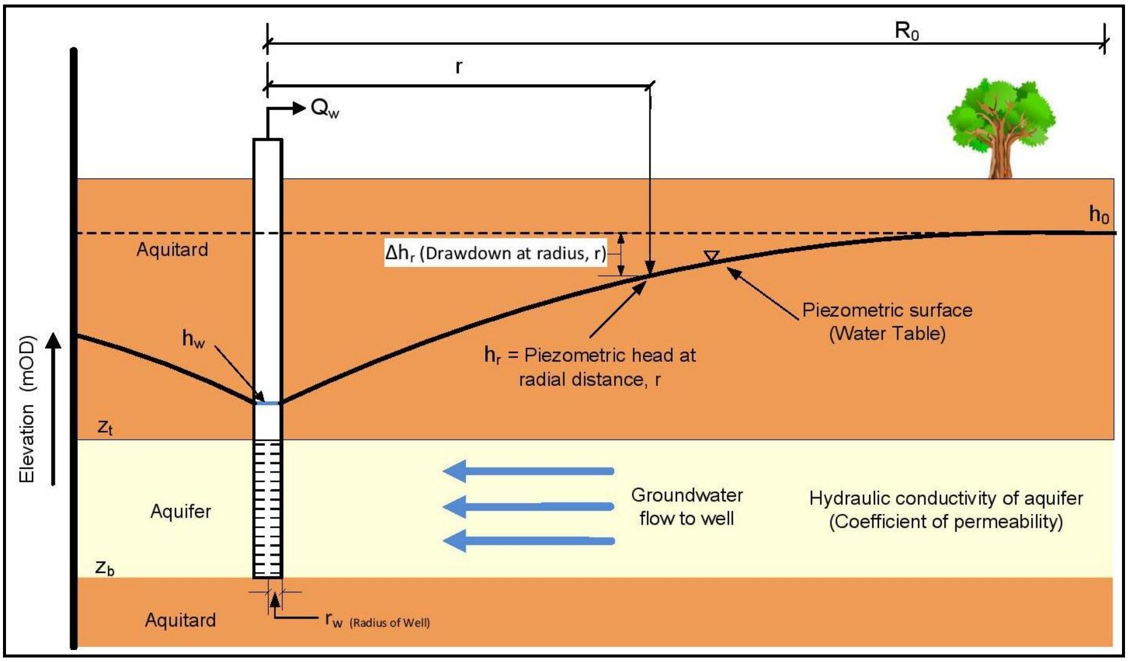


***Figure 25:** Description of the drawdown of the piezometric surface from a pumping well*

Thiem (1906) a radial flow solution to a well in a confined aquifer (Figure 25) as

$$Q_w = \frac{2\pi bk}{2.303} \frac{(h_o - h_w)}{Log_{10}(R_o/r_w)} \tag{15}$$

From which hydraulic head, h_r, at distance, r, from the borehole centre be calculated as:

$$h_r = h_w + (h_o - h_w)\frac{Log_{10}(r/r_w)}{Log_{10}(R_o/r_w)} \tag{16}$$

Dupuit-Forchheimer conditions applied to groundwater flow in an unconfined aquifer

Groundwater flow through an unconfined aquifer with a phreatic (free) surface, or water-table, has some degree of two dimensional behaviour. This means that in addition to a hydraulic gradient and Darcy Velocity in the radial direction, there is also a flow and gradient in the vertical, z, direction. However, solving the governing equations in two-dimensional (r, z) cylindrical coordinates is complex, especially for unconfined phreatic conditions. For this reason, scientists Dupuit (1863) and Forchheimer (1886), specified a condition which simplifies the equations from which a solution equation could be derived.

Known widely as the Dupuit-Forchheimer assumptions, or Dupuit simplification, this states that the vertical hydraulic gradient is effectively negligible for practical purposes, that is,

$$\frac{\partial h_w}{\partial z} \approx 0 \tag{17}$$

Based on the above simplification, the transmissivity can then be assumed to be the product of the permeability and the saturated thickness between the phreatic water-table surface, h_r, at a distance from the centre of the well, r, and the base of the aquifer z_b. That is,

$$T_r \approx k_r(h_w - z_b) \tag{18}$$

These conditions result in the reduced governing steady-state equation as follows:

$$\frac{\partial}{\partial r}\left[r(h_w - z_b)k_r \frac{\partial h_w}{\partial r}\right] = 0 \tag{19}$$

Solution for hydraulic head resulting from pumping from an unconfined aquifer

The above governing equation for groundwater flow towards a pumping well in an unconfined aquifer (19) was solved by Dupuit (1848) and Thiem (1906) to give the solution.

$$Q_w = \frac{\pi k}{2.303} \frac{(h_o - z_b)^2 - (h_w - z_b)^2}{Log_{10}(R_o/r_w)} \tag{20}$$

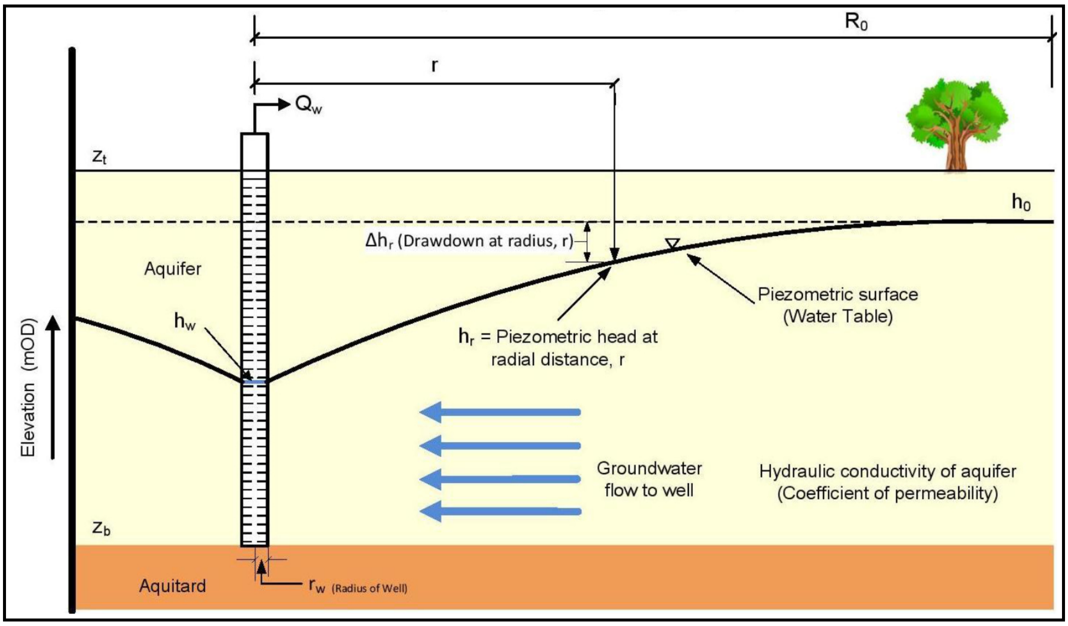


Figure 26. *Radial flow to a well in an unconfined aquifer*

From which the hydraulic head can be calculated from:

$$h_r = z_b + \sqrt{\Phi_r} \tag{21}$$

where

$$\Phi_r = \Phi_w + (\Phi_o - \Phi_w)\frac{Log_{10}(r/r_w)}{Log_{10}(R_o/r_w)} \tag{22}$$

with

$$\Phi_r = (h_r - z_b)^2,\ \Phi_w = (h_w - z_b)^2 \ and \ \Phi_o = (h_o - z_b)^2 \tag{23}$$

resulting in

$$h_r = z_b + \sqrt{\Phi_w + (\Phi_o - \Phi_w)\frac{Log_{10}(r/r_w)}{Log_{10}(R_o/r_w)}} \tag{24}$$

<u>Solution for hydraulic head when pumping from a mixed confined unconfined aquifer</u>

During construction dewatering, the piezometric head is often lowered to the extent that an original confined condition, becomes unconfined close to a groundwater abstraction well.

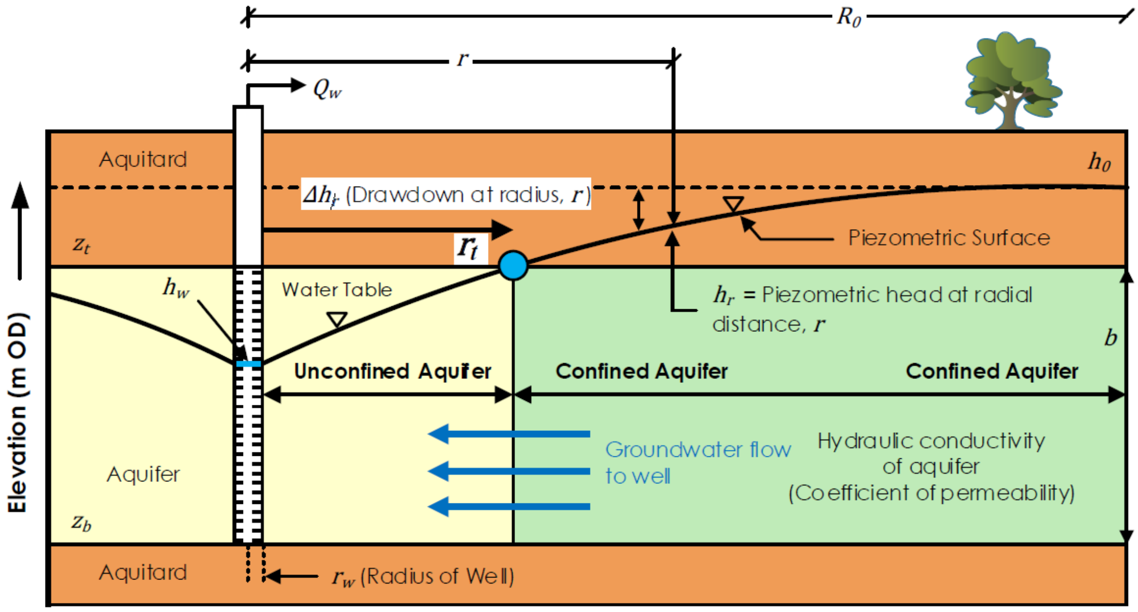


Figure 25. *Radial flow to a well in a mixed confined-unconfined aquifer (Thomas-Lai, 2024)*

$$Q_w = \frac{2\pi\alpha b k}{2.303} \frac{(h_o - z_t)}{\mathrm{Log}_{10}\left(\frac{R_o}{r_w}\right)} \tag{25}$$

where

$$\alpha = 1 + \frac{b^2 - (h_w - z_b)^2}{2b\,(h_o - z_t)} \tag{26}$$

$$b = z_t - z_b \tag{27}$$

$$r_t = exp\left[\frac{Ln(R_o) + \psi Ln(r_w)}{(1+\psi)}\right] \tag{28}$$

$$\psi = \frac{1}{\alpha - 1} \tag{29}$$

During confined conditions, where $r_t \geq r \geq R_o$

$$h_r = z_t + (h_o - z_t)\frac{Log_{10}(r/r_t)}{Log_{10}(R_o/r_t)} \tag{30}$$

and, during unconfined conditions, where $r_w \geq r \geq r_w$, and $\Phi_t = (z_t - z_b)^2 = b^2$

$$h_r = z_b + \sqrt{\Phi_w + (\Phi_t - \Phi_w)\frac{Log_{10}(r/r_w)}{Log_{10}(r_t/r_w)}} \tag{31}$$

<u>Verification of mixed confined-unconfined equation</u>

The above equation to determine the abstraction rate from a pumping well to maintain the well head at a specified head level (25), together with the subsequent reduced water table or piezometric head level at distance from the abstraction well (26) and (27), has been applied to a test problem below. In this test problem, the base of the aquifer is at 10m OD, the top of the aquifer at 20m OD, the initial artesian head at 30m OD, the head in pumping well at 12m OD, and with a coefficient of permeability of 1 x 10^{-5} m/s.

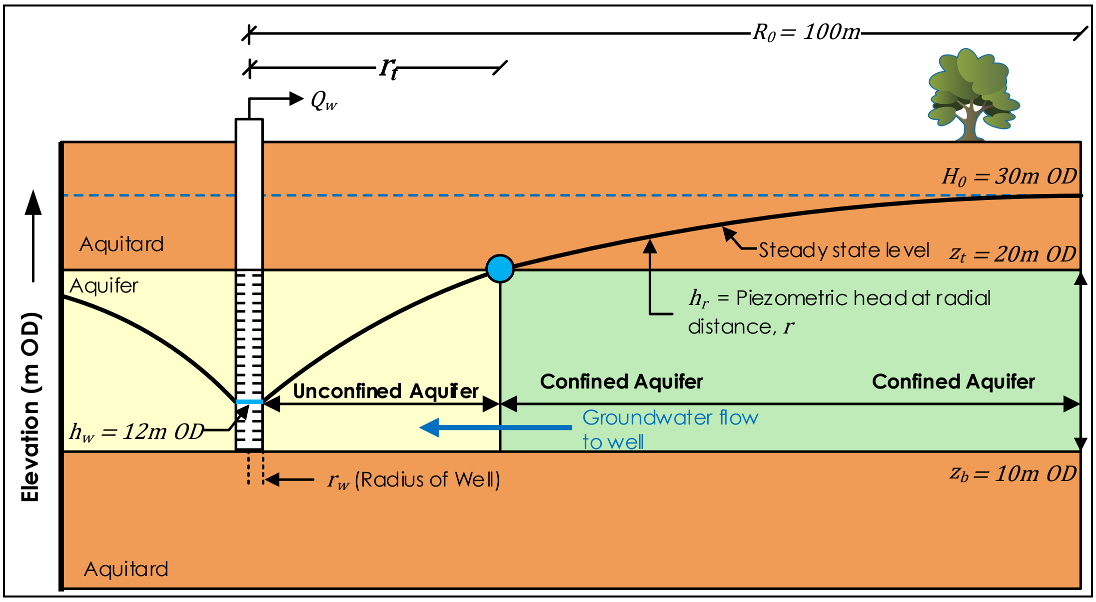


Figure 26. *Test problem of groundwater flow to a pumping well under mixed confined and unconfined aquifer conditions, with an aquifer coefficient of permeability as 1 x 10^{-5} m/s.*

Figure 27 depicts the three conditions: (i) a fully confined conditions (bottom blue line with Q = 16.37 Lit/s), (ii) fully unconfined conditions (top purple line with Q = 18.01 Lit/s) and (iii) mixed confined-unconfined conditions (middle red line with Q = 13.46 Lit/s). The red line is produced by a finite element model with the blue dots calculated by the above solution.

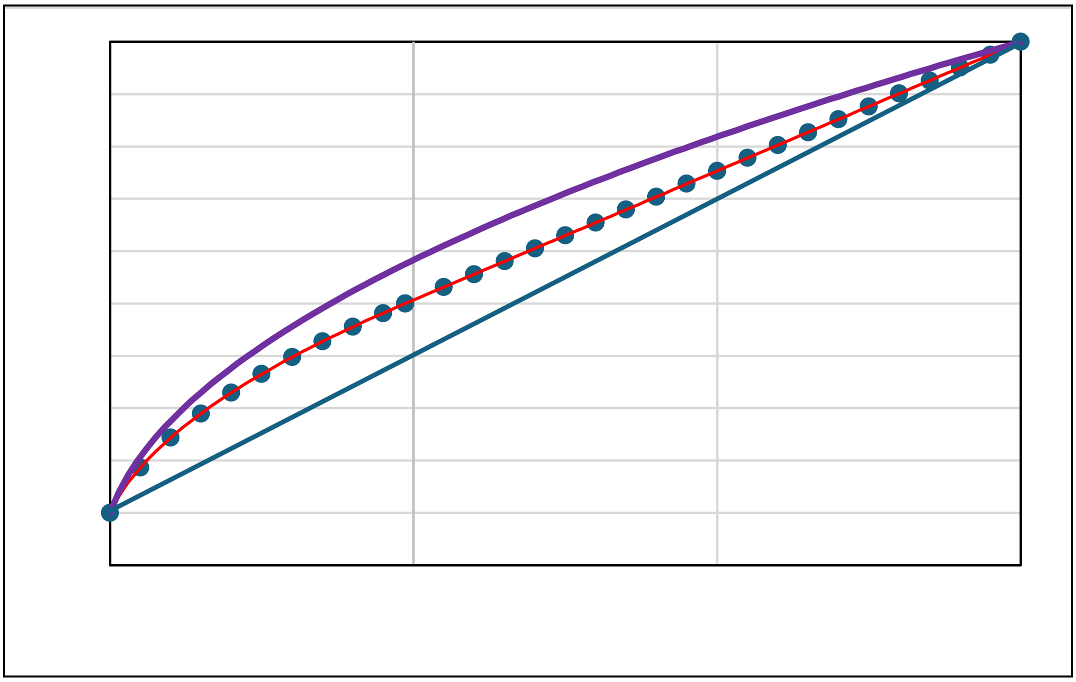


Figure 27. *© Stephen Thomas & Shiyi Lai. OGI Groundwater Specialists Ltd, Sept. 2024.*

Groundwater flow in multiple dimensions

Groundwater rarely flows through the ground in purely one dimension. Infiltration from surface recharge in the verical direction, aquifers can be hetereogeneoous and anisotropic, and abstraction from pumping wells can direct the groundwater in many directions.
Whilst hydraulic head h_w is a scalar (a zero order tensor), i.e. without direction, the spatial derivative of the hydraulic head, known as the hydraulic gradient, is a first order tensor, otherwise known as a vector. Thus the hydraulic gradient has direction.

$$I_x = \frac{\partial h_w}{\partial x} \qquad (32)$$

$$I_y = \frac{\partial h_w}{\partial y} \qquad (33)$$

$$I_z = \frac{\partial h_w}{\partial z} \qquad (34)$$

or in tensorial notation

$$I_j = \frac{\partial h_w}{\partial x_j} \qquad j = 1, 2, 3 \qquad (35)$$

Hydraulic conductivity (coefficient of permeability) is a second order tensor, i.e. a matrix, and in three dimensions, has nine components.

$$\begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} = k_{ij} \qquad i, j = 1, 2, 3 \qquad (36)$$

From the above, Darcy's law can be written as follows:

$$\begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} = -\begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} \qquad (37)$$

or in tensorial notation

$$W_i = -k_{ij} I_j \qquad i, j = 1, 2, 3 \qquad (38)$$

from which, Darcy's Law can be written in matrix format:

$$\begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} = -\begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \begin{bmatrix} \frac{\partial h_w}{\partial x} \\ \frac{\partial h_w}{\partial y} \\ \frac{\partial h_w}{\partial z} \end{bmatrix} \qquad (39)$$

or in tensorial notation

$$W_i = -k_{ij} \frac{\partial h_w}{\partial x_j} \qquad i, j = 1, 2, 3 \qquad (40)$$

Of relevance to understanding the behaviour of groundwater flow towards an abstraction well, is using the cross-sectional radial condition, or cylindrical coordinates.
Darcy's Law in two-dimension cylindrical coordinates can then be written as.

$$\begin{bmatrix} W_r \\ W_z \end{bmatrix} = -\begin{bmatrix} k_{rr} & k_{rz} \\ k_{zr} & k_{zz} \end{bmatrix} \begin{bmatrix} \frac{\partial h_w}{\partial r} \\ \frac{\partial h_w}{\partial z} \end{bmatrix} \qquad (41)$$

From which the steady-state governing equation can be written in the form:

$$\frac{\partial}{\partial r}\left[r k_{rr} \frac{\partial h_w}{\partial r} + r k_{rz} \frac{\partial h_w}{\partial z} \right] + \frac{\partial}{\partial z}\left[r k_{zr} \frac{\partial h_w}{\partial r} + r k_{zz} \frac{\partial h_w}{\partial z} \right] = 0 \qquad (42)$$

The Dupuit-Thiem equation (20) is used to calculate the lowered water-table level between an abstraction well and a specified radius of influence, subject to the maximum gradient restrictions described by Sichardt (1928). For a 10m initial head over an aquifer base, drawdown of 3.32m at a well radius of 100mm, permeability 1.0 x 10^{-5} m/s, and radius of influence at 100m, the calculated steady-state water-table is depicted in Figure 28.

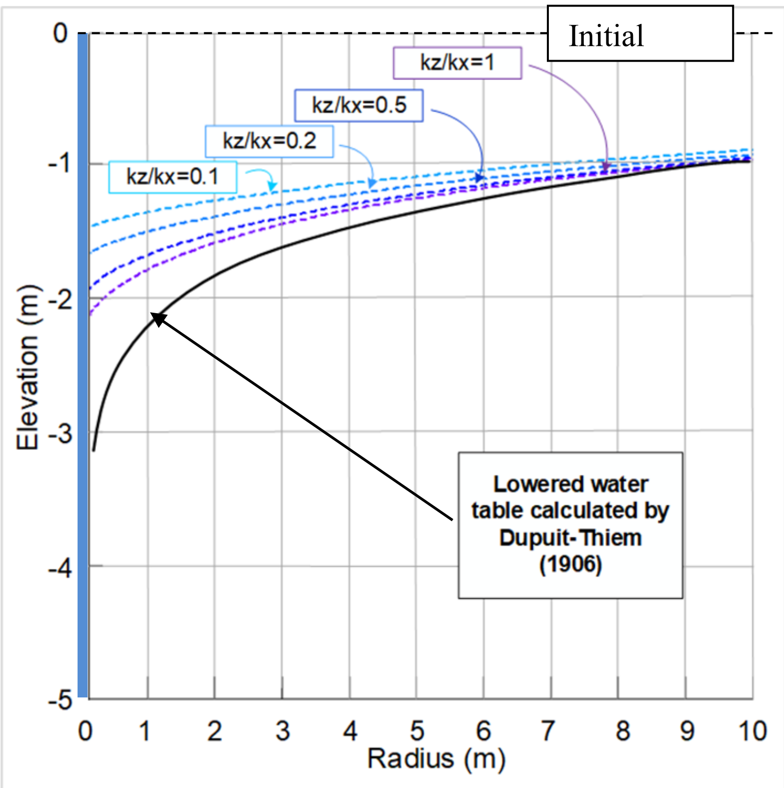


Figure 28. *Drawdown simulated using Dupuit-Thiem and Finite Element models*

The Dupuit-Thiem equation (20) is widely used in the groundwater control industry, due to the simplicity in calculating (i) the lowering of the water-table within an unconfined aquifer, and (ii) the rate of groundwater flow to an abstraction well. However, the limitation of the solution is a predominantly horizontal flow, with the vertical flow component effectively zero.

To illustrate the impact of this simplification used in practice, the same case problem is solved by the Finite Model SEEP/W (Geo-Slope International Ltd using axisymmetric cylindrical coordinates, solving the equations (42) above. An important consideration is that when assuming all flow is horizontal, the effect of the vertical permeability (k_{zz}) is not considered. However, for a hydraulic gradient at the well boundary as high as six, then the vertical permeability, input to SEEP/W as an anisotropy ratio, k_{zz}/k_{rr}, then becomes significant.

For this reason, a sensitivity analysis has been conducted using a range of anisotropy ratio, k_{zz}/k_{rr}, of 1.0, 0.5, 0.2 and 0.1 (Figure 28). It is important to also understand the difference in boundary condition at the pumping well boundary. In the Dupuit-Thiem solution, the hydraulic head is fixed at all points along the well boundary, and there is no mechanism for groundwater to enter at any other location other than the wetted length of the abstraction well. However, in the SEEP/W model, the well boundary condition above the water level in the well, but below the water table level calculated in the aquifer, is modelled as a seepage face. Along this boundary condition the water pressure is atmospheric with the hydraulic head specified at the elevation above the selected datum within the SEEP/W model.

As a result of this finite element sensitivity analysis, it is strikingly clear that the Dupuit-Thiem solution, which utilises the Dupuit-Forchheimer simplification, considerably over-estimates the drawdown in the region close to the groundwater abstraction well.

<u>Darcy velocity and continuity principles in deforming soils</u>

Within the field of geotechnology, under certain loading conditions, the porous material containing groundwater is often not rigid, and can regularly deform. Under such conditions, it is important to recognise that the pore-water velocity, i.e. the average velocity of the water through the pores, needs to be considered relative to the velocity of the soil particles, V_s.

Such relative velocity of the groundwater can be observed in the images below. In this soil embankment, there is groundwater issuing from the soil slope. However, there is also a deformation of the embankment itself in the form of slope failure. As a consequence, analysis of groundwater flow from the soil embankment, needs to also consider the relative velocity between the groundwater and the soil particles.

Figures 29 & 30. *Soil deformation as a consequence of slope embankment failure.*

<u>Darcy velocity in a deforming soil</u>

Figure 31 below describes the conditions of (i) the Darcy Velocity for the case of a static non-deforming porous medium, and (ii) for a deformable medium with a soil velocity, V_s.

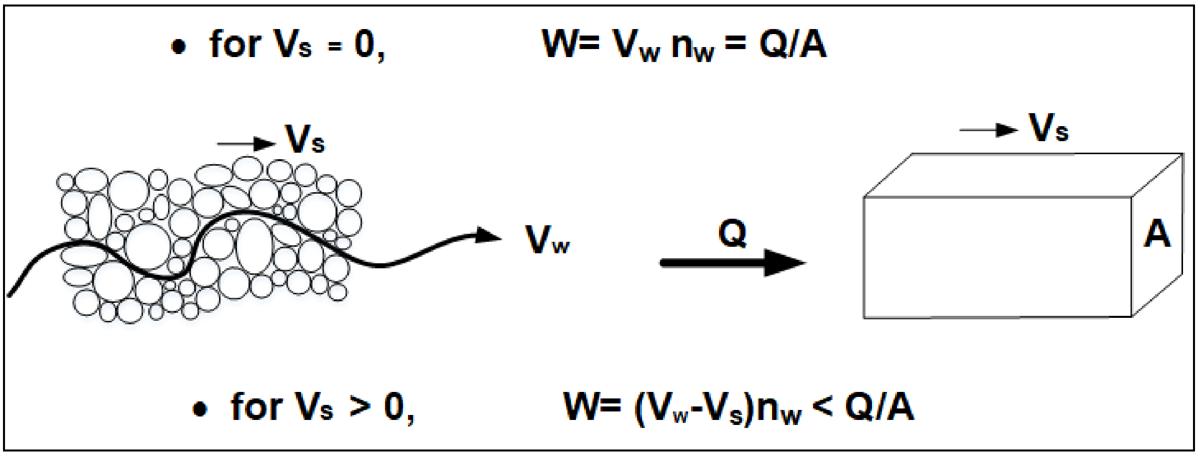


Figure 31. *Depiction of the relative velocity of pore-water for deformable soil.*

For a deforming porous medium, the Darcy velocity can be written

$$W = (V_w - V_s)n_w \tag{43}$$

And so, for a non-deforming porous medium, where $V_s = 0$ the Darcy velocity reverts to

$$W = V_w n_w \tag{44}$$

The relative velocity between the water and solid particles becomes particularly important to consider when solving geotechnical problems such as (i) consolidation, (ii) slope failure, and (iii) seabed loading. Without considering into account the velocity of the solid, the magnitude, even the direction of the water velocity can be incorrectly calculated.

<u>Principles of continuity of groundwater flow in deforming soils</u>

Biot (1941) developed the principles of continuity and equilibrium for a deformable material, known as a “poro-elastic” material. Within this derivation for deformation in the x-dimension, the principle of continuity of mass applies applies to both solid phase and water phases.

For the solid phase, where the solid particles themselves are considered incompressible,

$$\frac{\partial}{\partial x}(V_s n_s) + \frac{\partial n_s}{\partial t} = 0 \tag{45}$$

Where n_s is the solid volume ratio, this being $(1 - n_w)$ for saturated conditions, gives

$$\frac{\partial}{\partial x}[(V_s(1 - n_s)] - \frac{\partial n_w}{\partial t} = 0 \tag{46}$$

and for the water phase,

$$\frac{\partial}{\partial x}(V_w n_w) + \frac{\partial n_w}{\partial t} + \frac{n_w}{\rho_w}\frac{\partial \rho_w}{\partial t} = 0 \tag{47}$$

Adding (46) & (47) together, yields

$$\frac{\partial}{\partial x}[V_s(1 - n_w) + n_w V_w] + \frac{n_w}{\rho_w}\frac{\partial \rho_w}{\partial t} = 0 \tag{48}$$

$$\frac{\partial}{\partial x}[V_s] + \frac{\partial}{\partial x}[n_w(V_w - V_s)] + \frac{n_w}{\rho_w}\frac{\partial \rho_w}{\partial t} = 0 \tag{49}$$

From which

$$\frac{\partial}{\partial x}\left[\frac{\partial w_x}{\partial t}\right] + \frac{\partial}{\partial x}W + c_w \gamma_w n_w \left[\frac{\partial h_w}{\partial t}\right] = 0 \tag{50}$$

Where c_w is compressibility of water, and γ_w is weight density of water. The term w_x is the displacement of the soil particles in the x-direction, with $\frac{\partial w_x}{\partial t}$ being the soil velocity, V_s. Incorporating Darcy’s Law (40) in the equation (50), and rearranging the last term, yields

$$\frac{\partial}{\partial z}\left[k_x \frac{\partial h_w}{\partial x}\right] = c_w \gamma_w n_w \left[\frac{\partial h_w}{\partial t}\right] + \frac{\partial}{\partial t}\left[\frac{\partial w_x}{\partial x}\right] \tag{51}$$

In this equation, there are two dependent variables to solve, (i) the hydraulic head, h_w, and (ii) the soil displacement, w_x. To solve for these variables, there needs to be an additional equation. This is the equilibrium equation, in this case presented in the x-direction.

$$(\lambda + 2G)\frac{\partial^2 w_x}{\partial x^2} - \gamma_w \frac{\partial h_w}{\partial x} = 0 \tag{52}$$

Biot (1941) equilibrium and continuity equations for a poro-elastic material

The fully three-dimensional equations that govern equilibrium and continuity in a deformable poro-elastic material, as derived by Biot (1941), are presented in tensorial notation as:

$$\lambda \frac{\partial}{\partial x_i}\left[\frac{\partial w_j}{\partial x_j}\right] + G\frac{\partial}{\partial x_j}\left[\frac{\partial w_i}{\partial x_j} + \frac{\partial w_j}{\partial x_i}\right] - \left[\frac{\partial u_w}{\partial x_i}\right] = -F_i \qquad i,j = 1,2,3 \tag{53}$$

Representing equilibrium in three dimensions, and

$$\frac{\partial}{\partial x_i}\left[\frac{k_{ij}}{\gamma_w}\left(\frac{\partial u_w}{\partial x_j} - \gamma_w e_j\right)\right] = c_w n_w \left[\frac{\partial u_w}{\partial t}\right] + \frac{\partial}{\partial t}\left[\frac{\partial w_i}{\partial x_i}\right] \qquad i,j = 1,2,3 \tag{54}$$

representing water & solid particle continuity, with u_w as pore-water pressure, λ and G as Lame’s elastic constants, e_j the unit gravitational vector, and F_i as the body force vector.

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MANAGING ABSTRACTIONS IN IRELAND: THE END OF THE BEGINNING OR THE BEGINNING OF THE END?

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ABSTRACT

New abstraction legislation to control and manage water abstractions in Ireland was introduced in 2024. This legislation provides a mechanism to identify environmentally unsustainable abstractions, which can be conditioned to become sustainable through a licensing regime, and provides the basis for managing all other abstractions. The EPA have been tasked with licensing these abstractions and determining the volumes that can be sustainably abstracted from rivers, lakes and groundwater.

In developing sustainable hydrological (and hydrogeological) limits for rivers, lakes and groundwater, the EPA has considered the WFD environmental objectives for each water body, with an overall objective of developing hydrological supporting conditions that will sustain healthy ecology in rivers, lakes and wetlands.

The legislation is complex, and this paper provides a summary of the legislation, covering abstraction registration, exempted abstractions, general binding rules and licensing. An overview of the significant abstraction assessment criteria that will be used to determine if an abstraction is environmentally sustainable is included, although ultimately detailed site specific assessments and monitoring data gathered by the abstractor will be critical when it comes to demonstrating environmental sustainability.

Key words: *Ireland, water resources, abstractions, legislation, groundwater*

INTRODUCTION

In August 2024, legislation, dedicated to the control and management of water abstraction, was introduced in Ireland. The legislation introduces a registration, licensing and control regime for water abstractions and associated impoundments.

Just over half of the registered abstractions in Ireland are for the provision of drinking water. Overall, excluding hydropower abstractions, registered groundwater abstractions make up approximately 8% of the total volume of water abstracted in Ireland. However, groundwater abstractions are numerous and are critically important, with over 70% of registered abstractions coming from boreholes or springs.

This paper summarises the legislative requirements and the technical assessment criteria to be used in the new abstraction management regime.

LEGISLATIVE OVERVIEW

The Water Environment (Abstractions and Associated Impoundments) Act 2022 and associated Water Environment (Abstractions and Associated Impoundments) Regulations came into operation in August 2024.

The new legislation repeals:

- the Water Supplies Act 1942.
- section 4 of the Local Government (Sanitary Services) Act 1964.

- subsections (2) and (8) of section 9 of the Local Government (Water Pollution) Act 1977.
- the (Water Policy) (Abstractions Registration) Regulations 2018.

Transitional arrangements allow for existing Uisce Éireann abstractions to continue, as per the 1942 Act, and for existing arrangements between Uisce Éireann and the Electricity Supply Board, as per the 1964 Act, until the EPA makes a licensing decision.

The legislation does not repeal or amend the various Electricity Supply Board Acts and Orders, or the Canals Acts implemented by Waterways Ireland. Rather, and in a broad sense, the legislation states that the EPA shall have regard to the statutory functions conferred to the Electricity Supply Board and Waterways Ireland when regulating abstractions operated or managed by the Electricity Supply Board and Waterways Ireland.

The local authority register of abstractions referred to in the 1977 Act and the 2018 Regulations are fully repealed, with abstraction registration now included in Part 4 the 2022 Act. Part 4 of the 2022 Act introduces a small number of additional abstraction registration elements e.g., relating to associated impoundments and the publication of information contained in the register.

THE NEW ABSTRACTIONS LEGISLATION

In total three sets of regulations relating to abstractions and associated impoundments were enacted in 2024. Broadly, the first (S.I. 417/2024) was a commencement order for the 2022 Act, the second (S.I. 418/2024) was a schedule on licensing fees and the third (S.I. 419/2024 - hereafter referred to as "the Regulations") covers registration, exempted abstractions, "general binding rules", and the licensing regime.

The 2022 Act defines water abstraction as the removal or diversion of water. An associated impoundment means a structure (including a dam or weir) upon which the abstraction depends, which is situated in the water and is maintained for the purpose of the abstraction, whereby the water level or flow in surface waters or the continuity of the morphological condition is changed.

Abstraction from coastal water is not regulated under this legislation and these abstractions do not require registration or licensing by the EPA.

Rainwater harvesting is not considered an abstraction. This includes the collection of rainwater in lined ponds, which is a practice used at some golf courses and race courses. Rainwater that collects in quarry floors and is pumped away is not considered an abstraction under these Regulations, but pumping to lower the water table in a quarry is an abstraction.

REGISTRATION

As per the 2018 Regulations, abstractors are required to register with the EPA if they are abstract >25 m^3/d at any time. The new legislation introduces a few new elements, which are:

- Previously, abstractors could register multiple abstractions under one registration if the abstractions were part of the same scheme and hydrologically / hydrogeologically in continuity within a river sub-catchment. The new legislation requires separate registrations if the abstractions are from different water body types i.e., a borehole and river abstraction forming part of the same scheme require separate registrations.
- If an abstraction is dependent on an impoundment the abstractor should refer to this impoundment when registering. This is unlikely to be applicable for most groundwater sources, but some spring sources use impounding structures to create a sump.
- The published abstraction register is to be updated to include linkages to licensing e.g., licence granted, licence application submitted, registration only (no licence required) etc. with information to be made available in a similar manner to the other

EPA licensing regimes. Abstractions have been added to the Licence and Enforcement Access Portal (https://leap.epa.ie/).

- Note that, as per Article 10(4)(iii) of the Drinking Water Regulations (S.I. No. 99 of 2023), geo-references for drinking water abstractions will not be published.
- To ensure GDPR compliance, no information that can identify an individual person, as opposed to a business, organisation or company, will be published.

Each of the 1,800 registered abstraction operators, registered under the 2018 Regulations, have been contacted and asked to review, and where necessary, update their existing registered information.

Details on how to register or update an abstraction, are available on the EPA website at:

https://www.epa.ie/our-services/licensing/freshwater--marine/water-abstraction/how-to-register-and-update-a-water-abstraction-registration-/.

EXEMPTIONS

Part 3 of the 2022 Act introduces exemptions for certain categories of abstraction. The high level requirement is that all exempted abstractions will not cause the environmental objectives of water bodies to be compromised.

These exempted abstractions do not need to be registered with the EPA, but they may require authorisations e.g., through planning, and best practice should be applied in terms of the design, construction and operation of these abstractions. Further details are contained in Part 4 of the Regulations. The exempted abstractions include:

- domestic drinking water supply.
- abstractions used for firefighting.
- temporary abstractions operating during construction and other civil works, with the assumption that these will operate under another authorisation regime e.g., under planning.
- abstractions for testing or investigative reasons e.g., hydraulic testing or sampling.
- abstractions that internally transfer water between abstraction points that are already registered / licensed.

If the abstraction falls into one of these categories, and operates for less than 8 weeks or if it is lower than 25 m^3/day, then it is exempt from the Regulations. Overall, the expectation is that the exempted abstractions should be carried out in a manner that does not negatively impact water quality, cause a barrier to the passage of fish or disrupt the migration of sediment.

GENERAL BINDING RULES

Part 2 of the 2022 Act outlines a series of environmental factors where “best practice” should be applied. These are “general binding rules” that, with the exception of exempted abstractions, are applicable for all abstractions, irrespective of size.

The Regulations expand on these environmental factors, and in several cases the EPA is asked to produce supplementary guidelines. Abstraction operators not requiring an EPA licence will be required to operate in line with these best practice guidelines, and public authorities will be able to apply this guidance if they suspect an abstractor is operating their abstraction in a manner that is adversely impacting the environment.

The EPA is tasked with producing supplementary guidelines for abstractors and public authorities on how to measure or estimate the abstraction volume and abstractors should keep records to demonstrate the volume of water being abstracted, or the basis for estimated abstraction volumes, for the previous three years of operation. These records may be requested and examined by the EPA or other public authorities.

Abstractors should not carry out their abstraction at a rate that is likely to cause a barrier to the passage of fish or interfere with the transport of sediment within a body of surface water and should maintain any pipework, storage tanks or other equipment associated with an abstraction to keep water leakage to a minimum.

Article 8 of the Regulations tasks the EPA with producing ecology-based hydrological limits to sustain surface waters, controls to protect groundwater (Article 10), with abstractors instructed to meet the obligations of the Groundwater Regulations (S.I. 9 of 2010) and any EPA advice in relation to borehole construction and decommissioning.

ABSTRACTION LICENSING

The EPA is the competent authority for implementing a licensing regime for water abstractions.

For existing abstractions greater than 2,000 m^3/day, a licence application to the EPA was required by 28 February 2025 (unless an extension was approved by the EPA following a request by the applicant). As of March 2025, no applications were received by the EPA, but an extension had been requested for 95% of the registered abstractions that are greater than 2,000 m^3/day.

Once applications are received, as with other licensing regimes, the EPA will examine the application, request further information (if required), consult with public authorities and when complete, publish the application on its website (https://leap.epa.ie/).

The EPA will issue a proposed decision within eight weeks of receipt of a complete application, which may be extended by eight weeks if deemed necessary. Anyone (including the applicant) can make an observation on a proposed decision within 28 days of the EPA notice of the proposed decision. All observations on the proposed decision and submissions on observations will be considered prior to the EPA issuing a final decision regarding the application.

If the final decision is to grant the abstraction, a licence will be issued containing conditions that need to be complied with.

A proposed abstraction that exceeds the licensing threshold cannot commence until an application has been made and a licence granted by the EPA.

Details on how to apply for an abstraction licence, are available on the EPA website at:

https://www.epa.ie/our-services/licensing/freshwater--marine/water-abstraction/how-to-apply-for-a-water-abstraction-licence/.

Significant Abstractions 25 m^3/day – 1,999 m^3/day

Under the 2022 Act, the EPA is obliged to carry out assessments (significant assessment and assessment of certain abstractions for retrospective EIA or EIA) to determine if an abstraction between 25 m^3/day and 1,999 m^3/day requires a licence.

Where the EPA determines that an abstraction is a significant abstraction, and a licence is required, an application must be made within six months of the significant abstraction determination.

Section 18 of the 2022 Act defines a significant abstraction as an abstraction, on its own or together (cumulatively) with other abstractions, that:

a) alters, or is likely to alter, the hydrological regime of a body of surface water or a body of groundwater such that the water body fails or is likely to fail to meet its environmental objectives;

b) alters or modifies, or is likely to alter or modify, the flow condition, continuity or morphological condition of a body of surface water as a result of the existence or operation of an associated impoundment, such that the water body fails or is likely to fail to meet its environmental objectives; or

c) causes or is likely to cause a protected area to fail to achieve its environmental objectives.

Surface water abstractions should not impact the hydrological regime of rivers and lakes, such that they cause flow continuity issues, morphological impacts, or detrimentally impact the relevant biological quality elements in those waters, where this would result in the environmental objectives of those water bodies not being met, or where they adversely impact on the condition of qualifying interests of designated European sites.

Groundwater abstractions should not cause long-term overabstraction from the groundwater body that leads to unsustainable falling groundwater levels, nor should they reduce the groundwater flow to hydrologically connected rivers, lakes or groundwater dependent wetlands (GWDTE), such that this causes the groundwater body to fail to meet its environmental objectives. Groundwater abstractions should not cause salt water / other intrusion of poor water quality or adversely impact on the condition of qualifying interests of designated European sites.

River Assessment

The river waterbody assessment determines whether adequate flow is being maintained to support and maintain a healthy ecology. Environmental flows (e-flows) and the river assessment approach was previously summarised in the 2019 IAH proceedings (Quinlan, 2019) and draft assessment outcomes for rivers were included in the 2020 IAH proceedings (Nitsche, 2020). The river assessment approach remains the same as outlined by Quinlan in 2019, and the EPA will be completing an updated assessment in 2025 for the ~1,500 registered abstractions with volumes between 25 m^3/day and 1,999 m^3/day.

Where the e-flow limit is breached for more than 15% (for good status objective rivers) or 5% (for high status objective rivers) of the total river waterbody length, and the individual abstraction volume is greater than 1% of the volume of water which can sustainably be abstracted from a river, then the abstractions contributing to the breach are identified as significant abstractions.

Lake Assessment

Water abstractions in and/or upstream of lakes may alter the natural range of water level fluctuations which in turn can impact lake ecosystem dynamics and ecological health. The shallow water habitat is important ecologically, supporting rooted plants (macrophytes) and other biotic species and lowering the natural water level. Increasing the extent of very shallow areas can impact biotic species and cause sediment erosion.

Where a lakes habitable zone area is reduced (due to abstraction) by more than 1% in high status objective lakes, or 5% in good status objective lakes, for more than 1% of the days in any year, the abstraction(s) is identified as a significant abstraction.

If detailed lake surveys and bathymetry are not available, where the ratio of the Q50 naturalised river outflow to the total net influence of abstractions and discharges (total abstractions minus total discharges) from within and upstream of the lake is greater than 0.1 (i.e., 10%), the contributing abstractions are identified as significant abstractions.

Groundwater Assessment

Groundwater abstractions, either alone or in combination with other abstractions, can directly impact groundwater resources, leading to an unsustainable lowering of groundwater levels or saline waters being introduced. Groundwater abstractions can indirectly impact surface water resources, which may alter the supporting conditions needed to sustain a healthy ecology in surface waters and GWDTE.

The approach and hydrological limits used to identify significant groundwater abstractions in Ireland have been in place for several years and are documented in the 2009 IAH proceedings (Daly & Craig, 2009).

Key updates to this approach (as set out in EPA, 2024) relate to the indirect impacts of groundwater abstractions on the supporting conditions needed to sustain a healthy ecology in surface waters and GWDTE.

Flow depletion modelling (Moe, 2024) indicates that groundwater abstractions will not pose a risk to achieving the environmental objectives of an associated surface water body or impact on the supporting conditions needed to sustain a healthy ecology in GWDTE, where:

a) The groundwater abstraction is less than 100 m^3/day and is abstracting from a poorly productive aquifer and the abstraction is situated in either i) a predominantly Low groundwater vulnerability setting, or ii) a Moderate groundwater vulnerability setting where subsoil permeability (as mapped by Geological Survey Ireland) is Low.

b) The groundwater abstraction is less than 250 m^3/day and greater than 150 m from streams, irrespective of groundwater vulnerability setting.

c) The groundwater abstraction is less than 250 m^3/day and is abstracting from a karst aquifer where the karst features have been extensively mapped, provided the abstraction is not within the estimated zone of contribution of a downstream/downgradient spring, stream or GWDTE.

d) The groundwater abstraction is less than 100 m^3/day and is greater than 250 m from the boundary of a GWDTE or habitat with a water dependent qualifying interest, irrespective of aquifer type and vulnerability setting.

For all remaining groundwater abstractions, the abstraction may indirectly deplete the volume of water in the river or GWDTE. The volume of water depleted will be a proportion of the total volume abstracted, as dictated by the hydrogeology and distance from the river or GWDTE.

Once the depleted volume is calculated, this volume should be applied to the cumulative surface water abstraction assessment or used to calculate flow or water level reductions in the GWDTE. Where there is an e-flow breach in the river or the groundwater dependent qualifying interests of the wetland have failed their condition assessment under the Habitats Directive, the groundwater abstractions are identified as significant abstractions.

Associated Impoundments

An “impoundment”, as defined in the Act, means the doing of anything whereby the water level or flow in surface waters or the continuity of the morphological condition of a body of surface water is permanently or temporarily changed by means of a structure, including a dam or weir. An “associated impoundment” is an impoundment on which an abstraction depends and cannot exist without.

Impoundments alter the natural distribution and timing of river flows in natural ecosystems and may also act as barriers to the movement of sediment and migration of aquatic species. The environmental impacts of impoundments can be considered within a hierarchical framework of interrelated effects. Bergkamp et al. (2000) distinguish first, second and third order effects. In general, the complexity of interacting processes increases from first, to third order impacts, as illustrated in Figure 1.

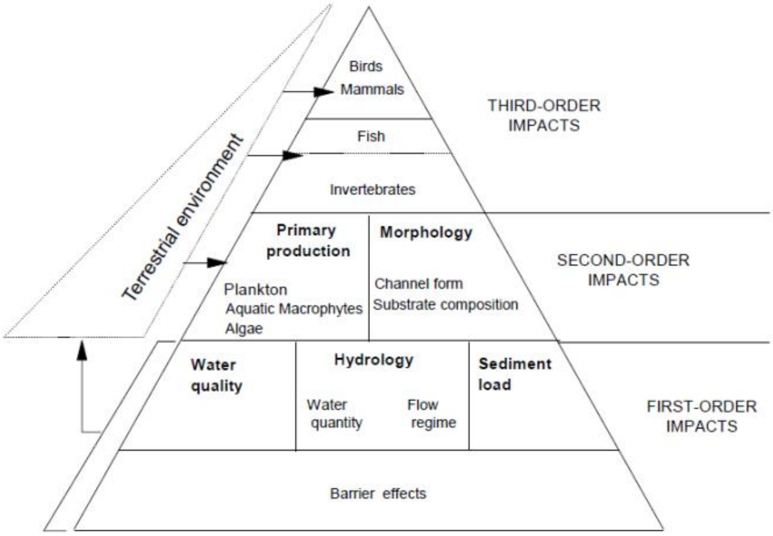

Figure 1: *Framework for assessing the impact of barriers on river ecosystems (Bergkamp et al., 2000)*

The size and nature of an associated impoundment may result in partial or complete environmental impact and may vary depending on the impoundment design / function itself and the prevailing flow conditions. Site-specific assessment is required by those carrying out the abstraction, to determine if an associated impoundment is causing environmental issues and to identify any measures that can be carried out to mitigate the issues.

Broadly these measures can be described as solutions to allow upstream and downstream passage of fish and other aquatic species at the impounding structure (e.g., a rock ramp or fish pass); flow related solutions to provide enough water to facilitate migration of aquatic species (e.g., spawning flows); and flows that allow the passage of sediment downstream (e.g., flushing flows). The overall flow regime for an associated impoundment may have many components. This may include ensuring the minimum e-flow is maintained at all times, with additional periodic releases of water, or seasonal releases of water to coincide with the migratory species spawning periods in the freshwater catchment (see Figure 2).

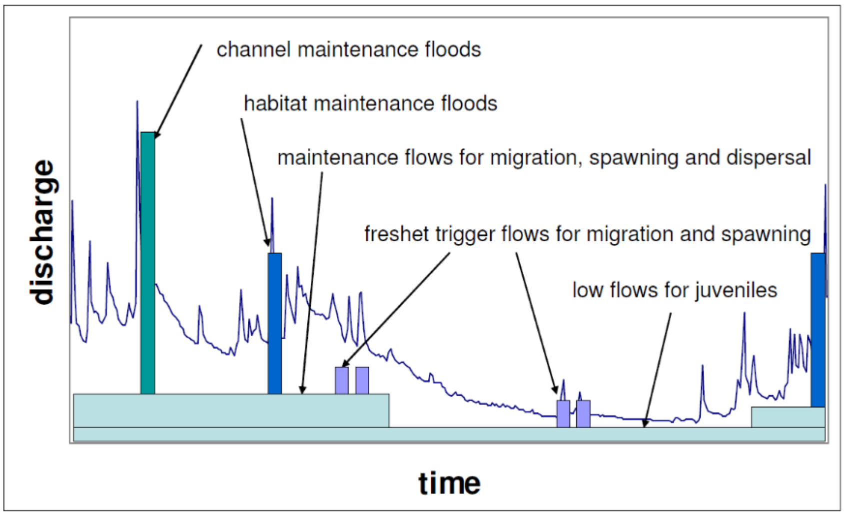

Figure 2: *Conceptual "building block" flow components required to deliver the environmental supporting conditions in rivers (SNIFFER, 2007).*

Given that bespoke, and often complex, assessments and solutions are required in relation to impoundments, all abstractions dependent on an associated impoundment, are required to apply for an EPA licence.

CONCLUSION

While in general Ireland has ample rainfall, the prolonged dry spells and droughts experienced in 2018, 2020 and 2022, inadequate water storage, increased demand for public water supply and commercial use, and future climate uncertainty, highlight vulnerabilities in our current management of abstractions.

The Uisce Éireann National Water Resources Plan highlights that it may take many years of management and planning before an environmentally sustainable and resilient public water supply system is fully operational.

Now, for the first time, Ireland has abstraction legislation that will facilitate the management of abstractions in a consistent manner. The abstraction licensing regime will ensure that all abstractions become environmentally sustainable, through the implementation of conditions that will provide suitable hydrological and hydrogeological supporting conditions for a healthy environment.

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LANDSLIDE GEOTECHNICAL REMEDIAL DESIGN INFORMED BY MULTI-DISCIPLINARY INVESTIGATION, TROEDRHIWFUWCH, WALES

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ABSTRACT

Troedrhiwfuwch, a derelict settlement in the South Wales Valleys, exemplifies the complex interplay of geotechnical and hydrogeological factors contributing to slope instability. The site is characterized by an active post-glacial landslide affecting the A469 highway, the sole north-south route in the upper Rhymney Valley. A remedial scheme aimed at stabilizing the road and ensuring safe access for local communities is under development.

This study discusses the findings from a comprehensive desk based assessment and ground investigation conducted between 2023 and 2024, which refined the site conceptual model. The investigation revealed the critical role of groundwater dynamics in slope stability, with continuous monitoring data highlighting the interaction of rainfall, groundwater, surface water, and slope movements.

Collaborative efforts between Tetra Tech and Coffey Geotechnics facilitated the integration of hydrological and geotechnical analyses, leading to the development of predictive site models for slope movements, both as rainfall thresholds for early warning systems, and under future climate change scenarios. The study underscores the necessity of interdisciplinary approaches in addressing complex geotechnical challenges and offers insights into effective investigation and remediation strategies for landslide-prone areas.

Key words: *landslide, slope stability, ground investigation, remedial design, South Wales, LiDAR, Rainfall Intensity Duration*

INTRODUCTION

Troedrhiwfuwch is the name given to a small but now largely derelict settlement in the South Wales Valleys, which was abandoned in the 1980's as ground instability and rockfalls threatened the village. The name is more commonly used to refer to the active post glacial landslide present at the former site of the village. The route of the A469 highway crosses the landslide close to the former settlement. It is the only north-south road link within the upper Rhymney Valley, forming part of the Strategic Highway Network, and linking the towns of New Tredegar and Pontlottyn.

Historically, there have been a number of slope movements at Troedrhiwfuwch which have affected the A469. The most recent movements occurred in 2014, when the A469 had to be closed for several months whilst emergency repairs were carried out, and more recently in February 2020, where significant damage to the carriageway and retaining walls were incurred following Storm Dennis.

Due to constraints within the Rhymney Valley, realignment of the route to avoid the landslip is not practical. Caerphilly County Borough Council (CCBC) have therefore received strategic funding from the Welsh Government's Resilient Roads Fund to allow for a remedial scheme to be formulated to stabilise the road, intended to maintain safe access for the communities along the existing road alignment. Tetra Tech and Coffey Geotechnics were commissioned by CCBC to undertake a preliminary design of the proposed remedial scheme. Tetra Tech provided ground investigation, highways, and drainage and hydrogeological consultancy services, Coffey provided geotechnical expertise and prepared the preliminary remedial design for stabilisation of the road.

BACKGROUND – LANDSLIDES IN SOUTH WALES

South Wales has one of the highest areal densities of landslides within the United Kingdom, with a particular concentration within the South Wales Coalfield. This is due to a combination of factors which combine to provide a high incidence of landslides:

- **Rainfall** – The Coalfield is subject to high rainfall. Long term total rainfall averages 1,200mm to 2,000mm, with monthly MORECS data indicating around 500mm to 600mm is lost to evapotranspiration, providing a potential effective rainfall of 600mm to 1,600mm (Robins et al., 2008).
- **Post-Glacial Topography –** Glaciation in the Quaternary led to the deepening and oversteepening of pre-glacial river valleys. The majority of landslides within South Wales developed thousands of years ago due to peri- and post-glacial climatic conditions. Residual movement in already failed slopes has continued until present times.
- **Geology –** Within the Coal Measures, contrasting lithological, strength and groundwater conditions prevail on valley sides. Strong and permeable jointed sandstones act as a reservoir for groundwater, and commonly overlie weaker, less permeable mudstone sequences; this provides favourable conditions for landslide development (see hydrogeology section)
- **Mining -** Mining subsidence is known to have reactivated faults and fissures within the coal field, especially on the well jointed Pennant sandstone plateaus. It is suspected that this subsidence may have led to reactivation of some extant landslides (Donnelly et al. 2000). The failure of colliery tips, some poorly sited or engineered, have led to later flow type slides, including the Aberfan disaster of October 1966; a more recent earth flow at Tylorstown in February 2020; and most recently at Cwmtillery in November 2024. In some cases, colliery spoil has been placed directly on existing mass movement deposits, or known areas of groundwater discharge, which was a contributing factor in the Aberfan disaster.

Troedrhiwfuwch is an example of a complex, deep seated post glacial landslide at which all of these factors have contributed to ongoing movement.

SITE SETTING AND DETAILS

LOCATION

The site context and overview is shown in Map 1 and Map 2, respectively. Two major lobes of land slipped material (vertical hatched areas) are present on this side of the Rhymney Valley, although only the northernmost lobe is active enough to affect the stability of the A469. The River Rhymney is located to the north-east of the landslip and carriageway; the fall of the topography is from the uplands of Y Darren in the south-west at around 420mAOD, to the River Rhymney at 210mAOD. The A469 carriageway is located at ~265mAOD. The Rhymney railway line, a major commuter route, is located between the River and the A469, and has also been affected by slope movement in the past.

Maps 1 to 5: *Contains data supplied by Ordnance Survey, Welsh Government and British Geological Survey.*
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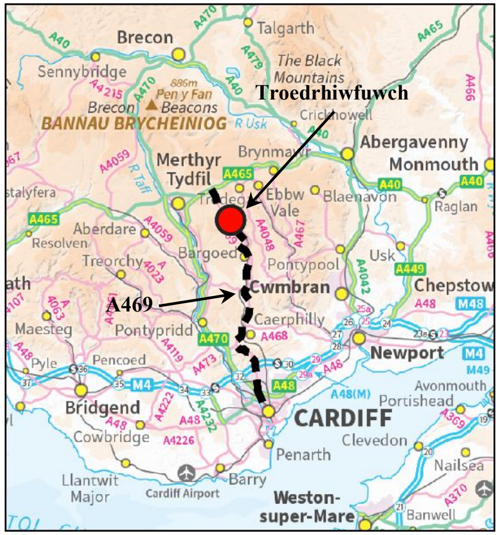
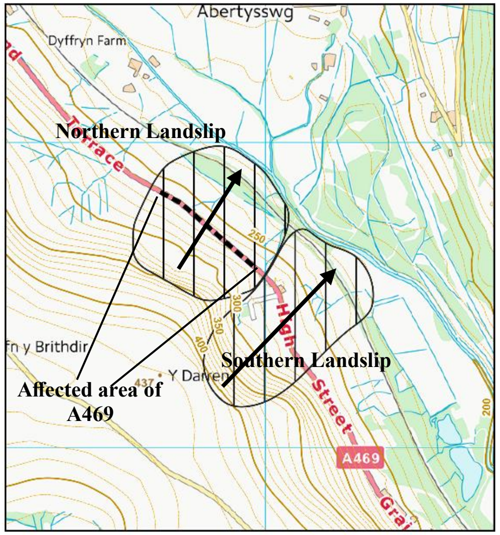
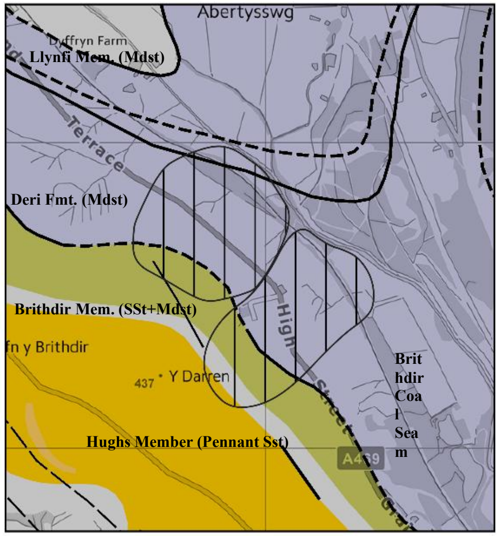


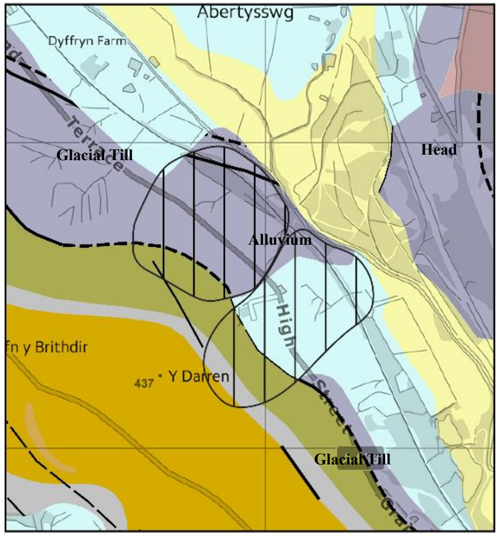
Map 1: *Site Context*



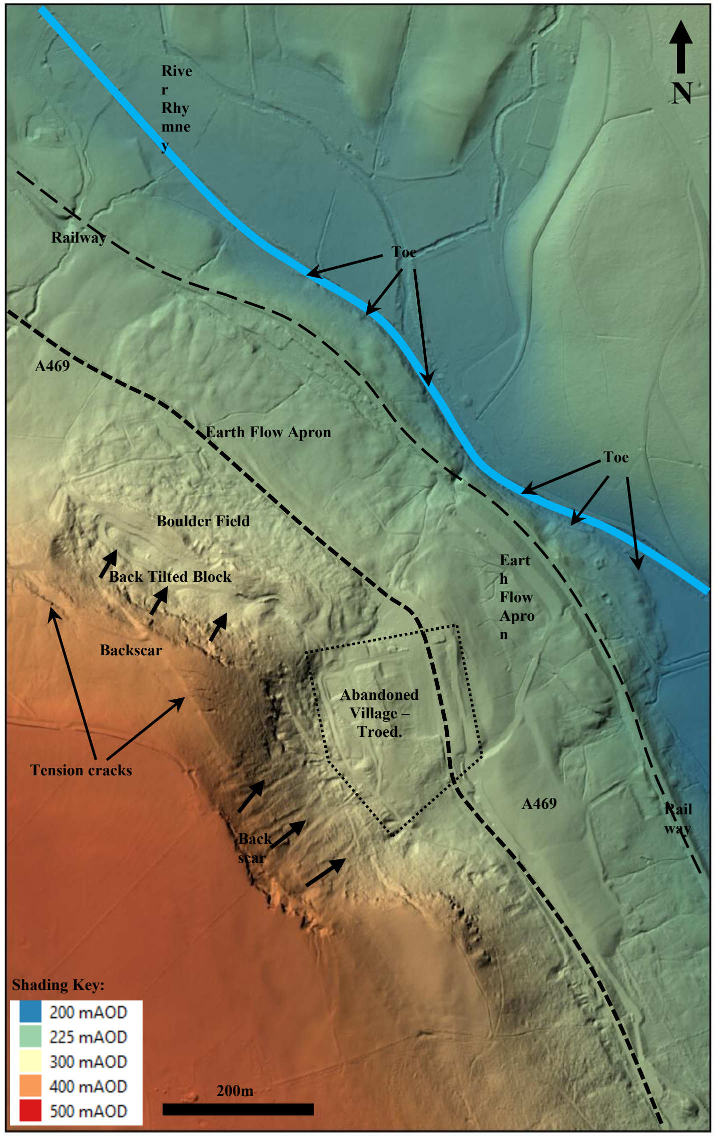
Map 2: *Site Overview*



Map 3: *Bedrock Geology*



Map 4: *Bedrock and Superficial Geology*



Map 5: *Welsh Gov. LiDAR Toposhade and Hillshade*

GEOLOGY

A map of published BGS bedrock geology is shown in Map 3. The bedrock geology comprises in descending order, the thickly bedded Hughs Member ‘Pennant’ Sandstone; The Brithdir Member, which comprises mainly sandstone with some mudstone and siltstone; and the predominantly mudstone Deri Formation. The Brithdir Coal Seam, a thick and productive coal seam with associated fireclay, is located between the Brithdir Member and the Deri Formation. It outcrops on the valley side, and is known to have been worked via adits in the driven into the hillside, including some located within the backscars of the landslips; the Tylacourt coal seam is also present beneath the Brithdir Seam Note how the marked outcrop of the seam correlated closely with the backscars of both landslip lobes.

Superficial and bedrock geology is shown in Map 4. Superficial deposits typical of the South Wales Valleys are present, with mainly cohesive Glacial Till present on the mid-slopes of the valley, spreads of Alluvium on the valley bottom associated with the River Rhymney, and patchy deposits of Head. The land slipped material itself is highly heterogenous, grading from intact slabs of displaced bedrock and boulders to clay; generally, it is coarser grained upslope, and fines downslope. It comprises slipped bedrock, and earthflow deposits which entrained the pre-movement superficial deposits.

HYDROGEOLOGY

The sandstone units within the Coal Measures are typically water bearing, with water stored and transmitted in fractures and fissures. The mudstones commonly act as aquitards, forming a multilayered aquifer system. Perched water tables can also develop within unconsolidated deposits, such as Glacial Till. One contributing mechanism to the formation of landslips in South Wales is the presence of saturated conditions at the mudstone-sandstone interface, and discharge of water to the slope below the interface. At Troedrhiwfuwch, the predominantly sandstone Hughs and Brithdir Members overlies the mudstone Deri Formation, with the original failure surface potentially developing in association with a weak coal or seatearth within the Brithdir and Tylacourt coal seams located at the junction of the two lithologies, under saturated conditions.

USE OF OPEN-SOURCE LIDAR DATA

An extract of Welsh Government aerial LiDAR data is presented in Map 5. Conspicuous features visible and annotated on the LiDAR hill shade include: the dilated tension cracks located on the uplands above the northern backscar; the two major landslide lobes and associated backscars; the back tilted bench representing a large rotated mass which has slumped and come to rest beneath the backscar of the northern lobe; highly mottled ground comprising an active boulder field upslope of the A469 on the northern lobe; the runout earth flow debris aprons, with toes extending to and dissected by the River Rhymney. The footprint and terracing of the abandoned village of Troedrhiwfuwch is also visible on the southern landslide lobe. There are few traces of a back tilted block on the southern lobe; it may have been obscured during the development of the settlement.

Two LiDAR datasets are available for Wales; one captured around 2015, and one in 2022. By subtracting the values of the newer raster tile from the older raster tile, this generates a difference heightmap over the time period. Even without correcting for systemic survey errors such as tilt or misalignment between survey dates, this can provide a rapid appraisal of areas of interest and recent slope movements.

Figure 1 presents an annotated LiDAR difference map of the northern lobe of the landslip. Negative values of the difference raster, where the ground surface has dropped, are shown in blue; positive values, where the elevations have increased, are shown in red.

Identification of areas of recent movement was used in planning the most recent phase of GI in 2024.

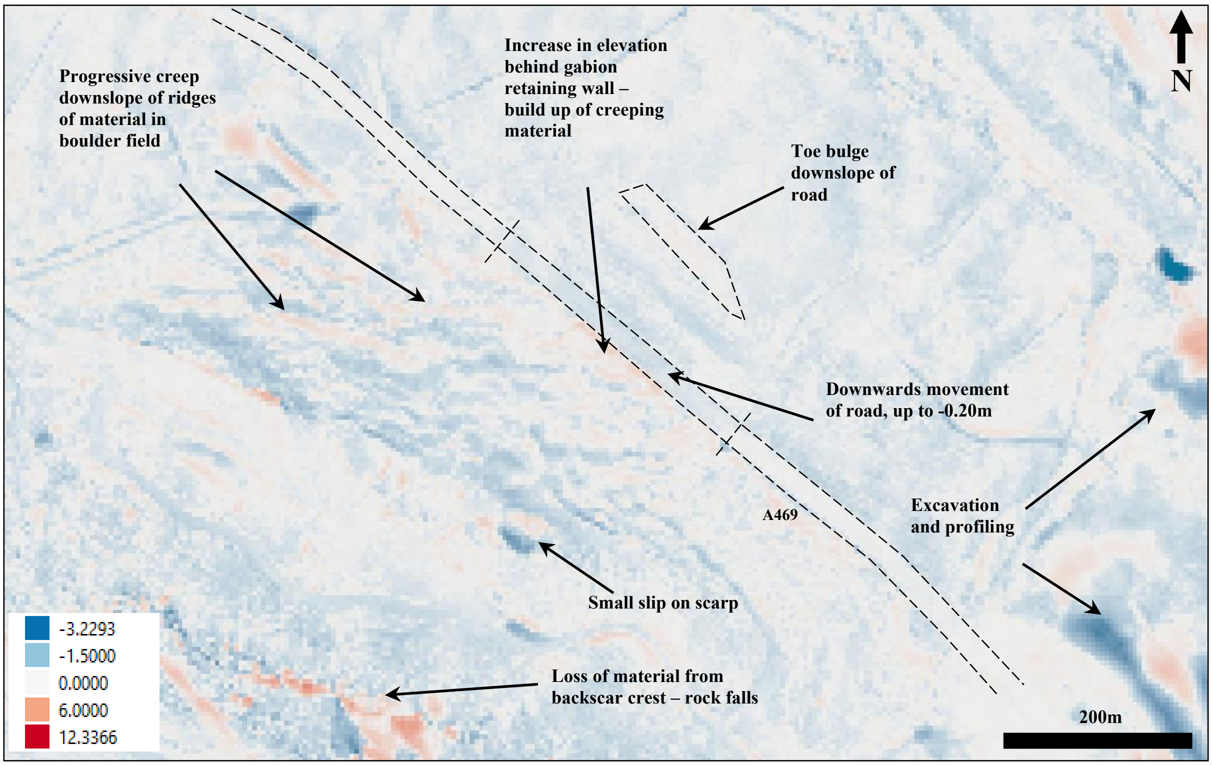


Figure 1: *Annotated LiDAR difference heightmap – change in ground elevations between 2015 and 2021. Contains Welsh Gov. and NRW data, reproduced under OGL. © Crown copyright 2025.*

HISTORY OF MOVEMENT

A history of ground movement at Troedrhiwfuwch has been recoded back to 1856; in 1906, a major slip damaged the railway line and anecdotally 'lifted the road up by ten feet'. The A469 has always been subject to deformation from creeping movement, with cracking of the surface strongly correlated with wet periods of winter rainfall and storm events. In the 1980's, the village was largely abandoned due to the threat of a major landslide; rock falls from boulders coming loose in the backscar, and creeping movement causing subsidence were also factors in the abandonment. Only two houses and the village war memorial remain today.

In 2001 there was a partial closure to replace a retaining wall that toppled due to a movement. Following Storm Darwin in 2014, a water main in the road burst and the carriageway was damaged. Following Storm Dennis in February 2020, a major toe bulge appeared in the slopes beneath the road; since then the road has had to be restricted to a single lane under traffic light control. Photographs showing the ongoing deterioration of the highway are provided in Figure 2.

GROUND INVESTIGATION

The site has been subject to several phases of ground investigation, dating back to 2016. Each ground investigation has built on the data provided by the previous investigation to inform the remedial design. The most recent phase of ground investigation, conducted over the winter of 2023 and 2024, with the focus on: developing and refining the site conceptual model to provide additional data for the remedial design, particularly in relation to the slope instability affecting the road; replacing damaged inclinometers and increasing the number of inclinometers; additional installation of continuously recording shape arrays; and installing piezometers and surface water flow meters for continuous monitoring, to develop the hydrogeological and hydrological understanding at the site.

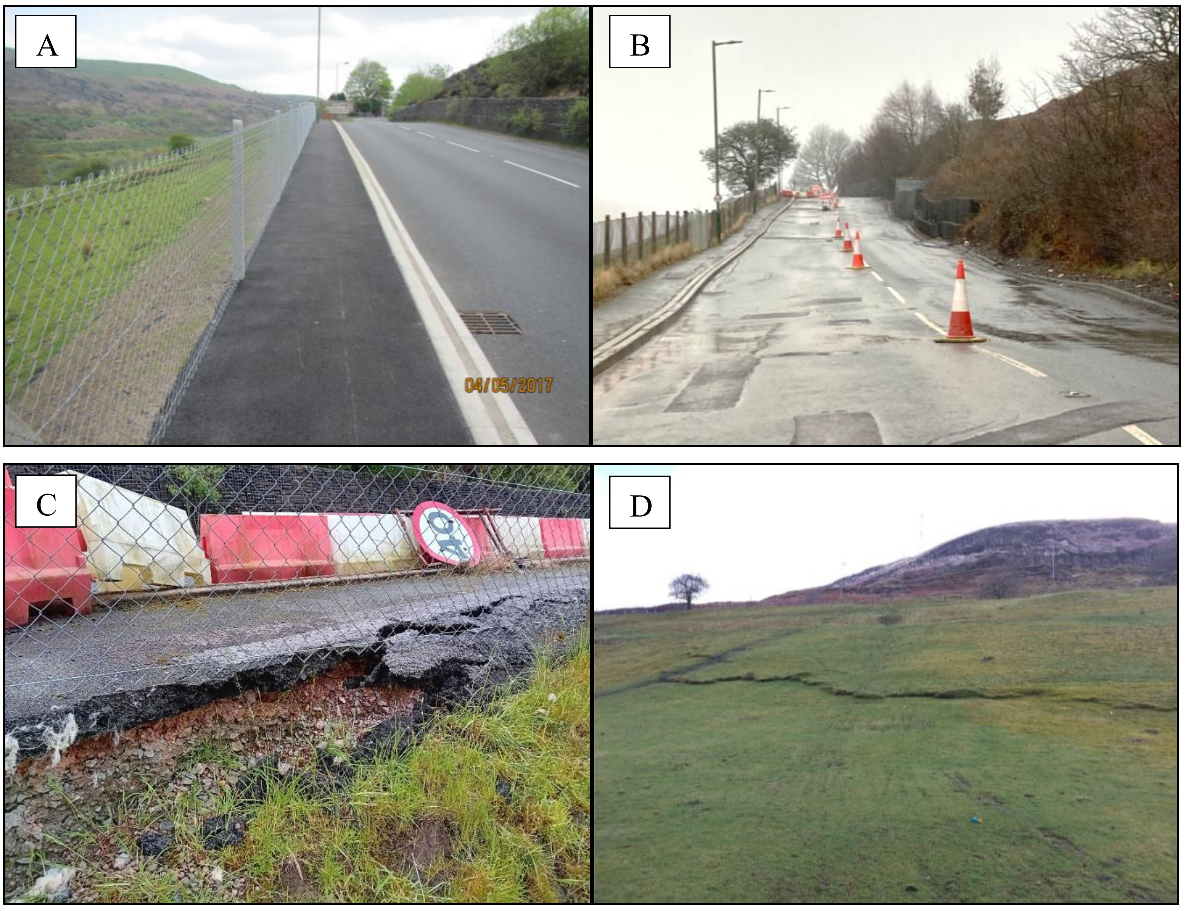


Figure 2: *Photos of A469 condition, clockwise from top left:* ***A****, road and pavement after reactive repairs in May 2017;* ***B****, compare with condition in February 2024, note kerb alignment and surface repairs;* ***C****, undermining of downslope edge of pavement due to progressive creep and material loss;* ***D****, toe bulge of moderate scale slip downslope of road in February 2020. Photo A courtesy of CCBC, C and D courtesy of Coffey.*

The refinements made to the site conceptual model (Figure 3) following the 2023/2024 ground investigation included:

- A full understanding of where slip surfaces were present within the landslip complex, based on rotary core, inclinometer and shape array data. Three general categories: Shallow, moderate and deep slip surfaces were identified.
- Remedial measures for the carriageway would need to be focussed on preventing damage to the road by moderate depth and shallow slip surfaces, both of which are active. The deformation of the pavement and existing gabion is being caused by movement both upslope and downslope of the road at these depths.
- Thankfully, the deep-seated slip surfaces are not presently active; it is unlikely that any economically feasible scheme would be entirely effective in preventing damage if they were to reactivate. Deeper slip surfaces are to be addressed by an early warning system allowing road closure in the event that significant future ground movements are observed.

- Eighteen months of continuous groundwater level and surface water flow monitoring data has been collected; zones of seepage and groundwater discharge were confirmed. Assessment of the groundwater hydrographs demonstrates that both shallow, perched groundwater and deeper groundwater within the bedrock is present on site. The perched groundwater bodies receive the majority of incipient rainfall on the site, and following rainfall events discharge this water either to springs and seepages, or as groundwater flows downwards to the deeper bedrock aquifer.

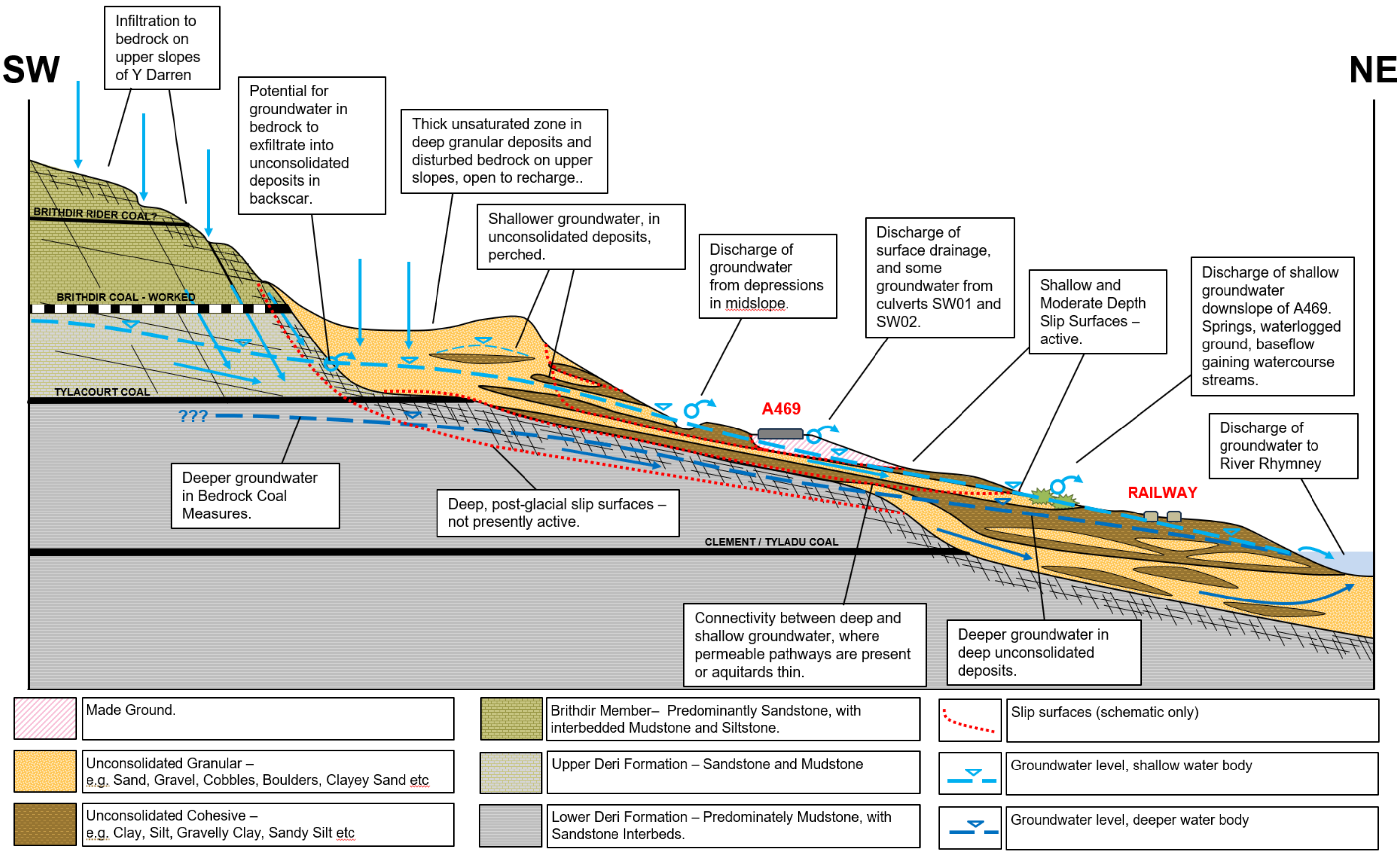


Figure 3: *Revised hydrogeological conceptual site model, incorporating findings from the 2023/2024 phase of ground investigation.*

CONCLUSION - CROSS DISCIPLINE SUCCESS STORIES

Due to the interaction between hydrological and geotechnical elements of the project, collaboration between disciplines within Coffey and Tetra Tech was crucial to arrive at the optimal remedial solution:

- Tetra Tech performed Kriging of the continuous groundwater monitoring dataset during different conditions including storm events captured over the winter of 2023/2024. This allowed for the generation of groundwater profiles which were utilised by Coffey in the slope stability assessments. These demonstrated that the slope was metastable, and highly sensitive to pore water pressures. This assisted with the back calculation and validation of key geotechnical parameters.

- Linear regression analysis conducted by Coffey on the groundwater dataset allowed for the prediction of increased groundwater levels under future climate change storm scenarios to be incorporated into slope analysis for the remedial design, via forecast climate change groundwater profile lines generated by Tetra Tech.

- Comparison by Coffey of shape array data and rainfall data, both recorded at 15 minute intervals, demonstrates a strong correlation between cumulative rainfall and slope movement (Figure 4).
- Building on work by Winter et al. (2019) and St John et al. (2023), Rainfall Intensity Duration (RID) analysis was undertaken by Tetra Tech undertaken by comparing rainfall data with movement detected in on-site shape arrays, and known historical slip events. A tentative rainfall threshold has been derived for the site, over which slope movement is more likely to occur.

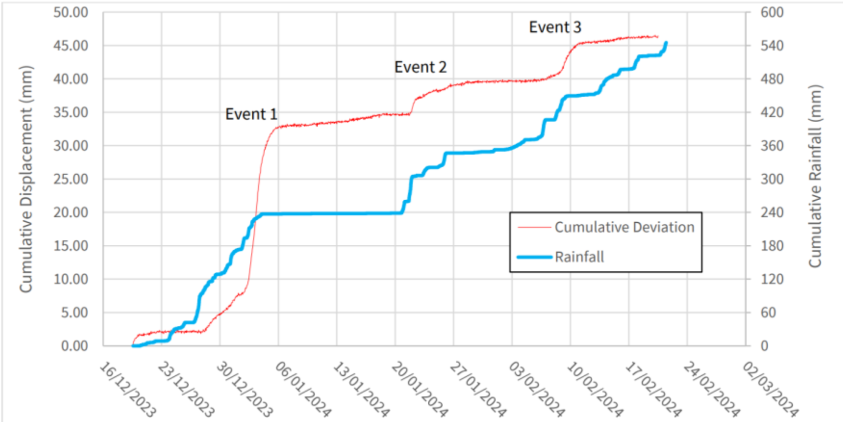


Figure 4: *Cumulative deviation (mm) in shape array installed within the A469 carriageway, versus cumulative rainfall totals (mm). Movements 1 to 3 correspond to storm events over two months during the winter of 2023/2024.*

- The RID threshold curve was incorporated into a draft early warning system for the site, utilising live NRW rain gauge data. This allowed for the successful forecasting of rainfall events where antecedent rainfall conditions made movement in the shape arrays, and damage to the A469 more likely to occur.

A preliminary remedial design for the highway was completed in May 2024. Proposed remedial measures for works along 500m of chainage include a contiguous piled wall on the downslope verge of the road; rock filled gabion walls on the upslope verge; and soil nailing plus installation of horizontal bored drains on the slopes above the road. The scheme is currently undergoing detailed design by Tetra Tech and Coffey.

ACKNOWLEDGEMENTS

Ariennir yn Rhannol gan
Lywodraeth Cymru
Part Funded by
Welsh Government

The Welsh Government's Resilient Roads Fund, which aims to address disruption to the highway network caused by severe weather, has funded the investigation and design of the remedial scheme for the Troedrhiwfuwch landslip affecting the A469.

I would like to express my sincere thanks to Caerphilly County Burrough Council for their support and permission to utilize the project in this conference paper, with special thanks to Kate Dowdall at CCBC. Many thanks to my colleagues Jane Belton, Andrew Smith, Richard Seddon and Jonah Dymond at Coffey for graciously allowing me to present extracts of their excellent geotechnical investigation and design work, plus site photos. Big thanks also to the team at Tetra Tech for their support during the project – Conor Lydon, Adam James, Erin O'Brien, James Craddock and John Holling.

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SESSION IV

HYDROGEOLOGICAL ASSESSMENTS TO DEVELOP GROUNDWATER FLOOD RELIEF MEASURES

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ABSTRACT

The increasing frequency of significant flooding events across Ireland underscores the necessity for robust flood defence schemes, particularly in urban areas where groundwater flooding poses unique challenges. This paper outlines a comprehensive approach to incorporating the groundwater component in the design of urban flood relief schemes. Detailed site investigations enabled the development of ground models and the conceptual understanding of the hydrogeological regime. This information was used to develop 2D seepage models which were tested through sensitivity analysis and calibration with site specific data. Predictive scenarios of the proposed flood defence measures were then incorporated into the model to assess the potential for groundwater seepage on the dry side. Where flow to surface on the dry side was identified the solutions firstly considered the potential for flow to filter drains and if this was not shown to be effective then considered a subsurface barrier.

While 2D modelling can be suitable for proposed flood defence measures located adjacent to surface water bodies that provide the driving head, it may not adequately capture the complexity of systems where groundwater seepage occurs away from surface water bodies. In such cases, as demonstrated in the Midleton FRS, a 3D model may be required. This highlights the importance of tailoring the modelling approach to the specific hydrogeological setting and flooding challenge.

Key words: *Groundwater* flooding*, groundwater modelling.*

INTRODUCTION

Significant flooding events in recent years across Ireland has prompted the need to design robust flood defence schemes able to protect communities and infrastructure. Groundwater flooding poses particular challenges necessitating innovative and effective defence strategies. Groundwater flooding occurs when the groundwater emerges at the surface. Groundwater flooding occurs when the water table rises to the surface, typically over a more extended period compared to other types of flooding. Unlike fluvial flooding, which can occur within hours, groundwater levels can increase over weeks or even months.

Groundwater flooding is often associated with turloughs located in Regionally Importance karstified bedrock aquifers. This flooding is captured in the GSI flood mapping identifying where groundwater flood relief measures may be required. However, groundwater flooding can also occur in combination with other types of flooding, necessitating consideration of the groundwater component in flood scheme design. This paper will describe the approach taken to account for the groundwater component in the design of the Lower Lee Flood Relief Scheme (FRS) and Midleton FRS which exhibit different groundwater flooding dynamics.

SITE INVESTIGATIONS

The first step in assessing the groundwater flood relief measures is to develop the ground model. Understanding the ground conditions and groundwater regime is key in developing the conceptual understanding and ensuring the appropriate flood relief measures are applied.

When designing the site investigations for flood relief schemes the following was taken into consideration:

The location of boreholes. Boreholes need to be located where flood defence measures are proposed as indicated by the flood mapping as well as in other strategic places to consider the groundwater flow patterns. The boreholes should penetrate through the overburden and into the bedrock, ensuring that some boreholes have response zones situated in the bedrock, while others are positioned in the gravel, alluvium, or other relevant strata.

Groundwater level monitoring including both manual groundwater depth measurements and longer-term high frequency automatic measurements with the use of in-situ data loggers.

Permeability tests including pumping tests, slug tests and infiltration tests to determine the local permeability of the underlying strata.

Surface water level monitoring locations allowing for the appropriate calibration of the models.

Geophysical surveys. In Midleton geophysical surveys in the form of ERT profiles were undertaken to supplement the information on the ground conditions from the boreholes and get a better understanding of the spatial variation of the gravel aquifer across a wider area. Geophysical survey identified areas of ‘weathered’ and ‘karstified’ limestone with clay infilled fractures throughout the study area.

Soil and rock logging and geotechnical testing to allow for geotechnical design of subsurface barriers and sheet piles.

PERMEABILITY TESTING

Groundwater flooding typically is associated with high permeability ground conditions which can act as preferential pathways for groundwater to emerge at the surface. Literature values can provide ranges in the order of magnitudes. Therefore, determining the permeability of the strata is important in achieving a better understanding of the groundwater regime and building more accurate seepage models. However, as the underlying strata are highly permeable this can lead to challenges in the field tests and the interpretation.

The standard geotechnical method for determining the permeability is slug tests. Some slug tests carried out in the gravel aquifer in Midleton showed response times in the order of seconds. In this scenario a water level loggers can be set to record at 0.5 second intervals to capture the response. This highlights the importance of using logger data and not relying on manual dip data. The response in some of these slug tests presented an oscillating (underdamped) signal which is representative of very high permeability strata. The standard Hvorslev is not suitable for analysing these tests. A critically damped solution such as the Springer-Gelhar (unconfined aquifers) or Butler Zhan (confined aquifers) (Duffield 2007).

High permeability gravels can also present challenges during pumping test analysis. For example, despite the very high pumping rate adopted (70m^3/hr) during pumping tests as part of the Lower Lee FRS site investigations, the drawdown observed in the pumping wells was limited (between 0.24m and 1.47m), which is indicative of the very high permeability expected. Furthermore, tidal signals evident in the groundwater levels during the pumping tests contributed to the challenge in analysing the data. As well as determining the permeability values using the Theis method in Aqtesolv the transmissivity was also estimated using the specific capacity in the Logan Approximation (Logan 1964) and from this the permeability was calculated by dividing by the aquifer thickness.

MODELLING PROCESS

This paper presents the assessment of the groundwater seepage using SEEP-W, a 2D finite element groundwater modelling software package, part of the Geostudio ground modelling suite. SEEP/W is a finite element software product for modelling groundwater flow in porous media. SEEP/W can model sophisticated saturated / unsaturated transient analyses with atmospheric coupling at the ground surface. SEEP/W is an industry standard package for these types of modelling project.

The standard groundwater modelling process (Anderson et al 2015) is outlined in the following steps:

- Conceptualisation,
- Data collection,
- Simulation and model calibration and validation,
- Prediction and uncertainly analysis.

The groundwater modelling was used to identify locations where there is a risk of seepage under the flood defences. The groundwater modelling adopted the following process to evaluate the most appropriate flood defence measures where groundwater flooding is possible:

Two-dimensional slice models were defined in areas where a flood defence is required. In areas with extensive flood defences, these were spaced at regular intervals to represent variations in the geological, hydrogeological and hydrological setting.

The 2D section was aligned parallel with the expected dominant groundwater flow direction during a flood event. In most cases this was perpendicular to river channel as during peak flood events the river is driving water into the aquifer and during the storm recession the flow as back from the aquifer into the river.

Each model was initially completed with no cut off wall under the flood defence to determine if there was a risk of groundwater flooding. Groundwater flooding was deemed to be an issue if the water table rose above ground surface during the course of the flood event.

Where the model indicates groundwater flooding would occur on the dry side, the seepage at ground surface were calculated to determine if the flow to surface could be accommodated within the drainage system. This is typically represented as a filter drain within a permeable trench, which can capture shallow groundwater and create a localised cone of depression adjacent the flood defence where the most significant groundwater flooding could be expected.

If the flow to surface could not be accommodated in the drainage system or if there was no groundwater drainage network proposed due to spatial constraints, a subsurface barrier was considered. In some cases, the presence and depth of the subsurface barrier was predetermined as part of the design due to engineering considerations for quay walls. At this point some sensitivity analysis was completed to determine the optimal depth of subsurface barrier which provides the required protection but not an unnecessarily long barrier to groundwater flow.

Flow through the urban drainage network (storm drains, leaky sewers, buried channels/canals) are not explicitly modelled as these were mainly considered to convey pluvial flood waters and will be captured by the pluvial flood defence measures. Where groundwater rises sufficiently high to infiltrate into these pipes this water will discharge with the surface water drainage in the pipes to their ultimate outfall location, which in the flood scenario would be blocked by a non-return valve and the water would report to a pumping station for discharge.

MODEL LOCATION

2D sections were developed for areas most at risk of groundwater flooding. As part of the Lower Lee FRS multiple cross sections throughout the project area were developed to ensure the variability in the ground conditions and proposed flood defence works was adequately represented. This allowed a quasi-3D consideration across the project study area as a whole as the response to individual sections to the same flood event could be observed.

Figure 1 illustrates how the water-table fluctuates over a series of tidal cycles across City Island in Cork. This shows that the groundwater level at either extreme of the model, directly adjacent to the north and south river channels is most influenced by the river level fluctuations. There is an inertial dampening of the tidal signal with increasing distance from the river as a result of storage within the aquifer. This illustrates how the highest risk for groundwater flooding is adjacent to the river. This directly influences the approach to groundwater flood defence which are focussed on the area immediately adjacent the river, including sheet piling under quay walls/embankments and filter drains on the dry side of flood embankments.

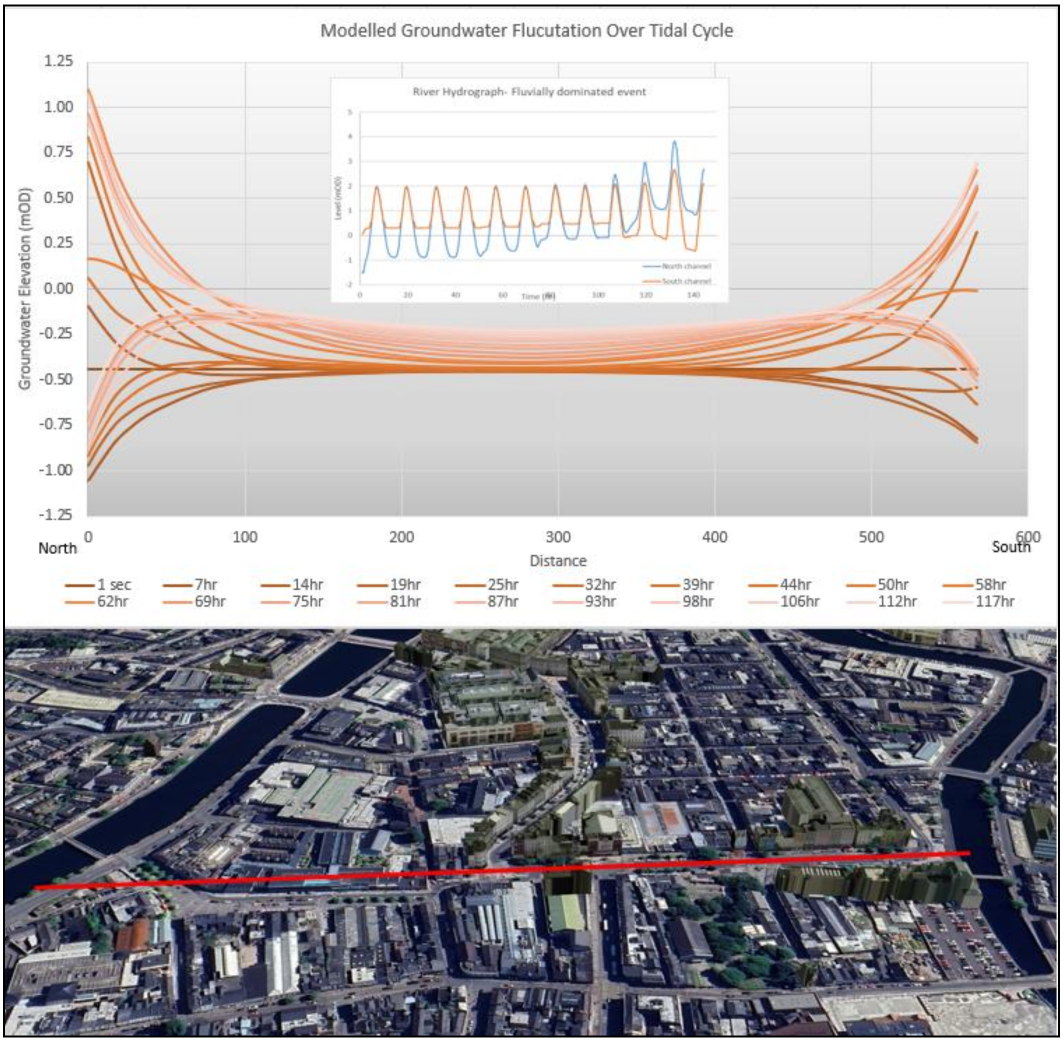

Figure 1: *Water table elevation across City Island in Cork over a series of tidal cycles*

PARAMETER SENSITIVITY ANALYSIS

Sensitivity analysis was completed to evaluate the sensitivity of the models to variations in hydrogeological conditions such as the permeability values and the presence or absence of an alluvial layer.

Sensitivity analysis carried out on models developed for the Midleton FRS highlighted the sensitivity of the model to the permeability value of the gravel as a driving factor for the flow rate into the drainage network. Table 1 shows the sensitivity analysis carried out on measured permeability values in the vicinity of the model location. This shows the influence the permeability of the gravel has at this model location on the resulting flow to the drainage network.

Table 1: *Sensitivity analysis of permeability values on flow rate to drain*

Model run	**Permeability (K) of Gravels (m/s)**	**Total Flow for total length of Flood Defence (l/s)**
Average k value	2.3×10^{-4}	10.81
Highest measured k value	5.6×10^{-4}	29.04
Lowest measured k value	7.1×10^{-5}	2.51

CALIBRATION

Calibration was conducted to verify the robustness of the model and the input parameters. The input parameters were calibrated in the model by comparing the modelled groundwater levels against the observed groundwater levels.

The Nash-Sutcliffe efficiency (NSE) model efficiency coefficient was used to assess the predictive accuracy of the model. NSE is a commonly used method for calibration of time series data, such as hydrograph fit assessment.

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right]$$

Where:

Y_i^{obs} is the ith observation value of the factor under evaluation,

Y_i^{sim} is the ith simulated value of the factor under evaluation,

Y^{mean} is the mean of the observed data,

n is the total number of observations.

NSE values can range from -∞ to 1, where 1 indicates a perfect fit. Values between 0 and 1 indicate an acceptable level of performance of the model and values of >0.5 indicate a “satisfactory” fit (Moriasi et al 2007).

An example of a calibration model is presented in Figure 2. Calibration of the models for the Midleton FRS achieved a NSE value of 0.85. Slightly lower modelled groundwater levels are accounted for by the fact that the tidal data used in the model was slightly downstream of the calibration point and therefore was lower than the tidal level at the point in the estuary directly adjacent to the calibration point.

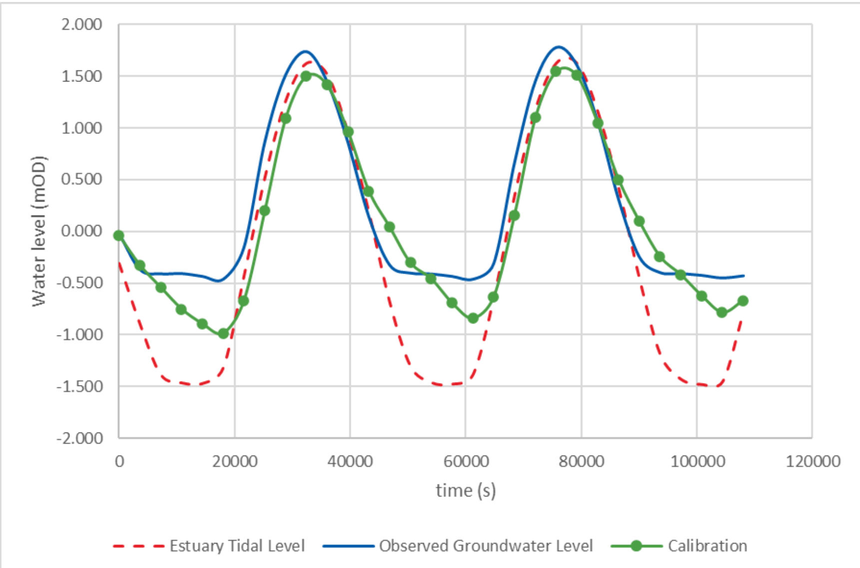

Figure 2: *Model Calibration with observed groundwater and tidal levels*

MODEL PREDICTIONS

When the base model is developed and calibrated the next step was to apply the flood defence measures in the flood scenarios. In an urban environment these can include embankments, walls, subsurface barriers or drainage. Each section was modelled under non-climate change and climate change flood hydrographs. The river hydrographs were provided from the hydraulic model for each specific section. Areas which were considered tidally influenced include tidally dominated hydrographs and were preceded by two tidal cycles to create realistic initial conditions.

Where flooding occurred on the dry side the first assessment considered if the predicted flows could be captured in a filter drain and accommodated by the drainage system, such as the example of the model and graphical output depicted in Figure 3. If this was not a viable option due to various constraints such as the space requirement for the filter drain or the capacity in the system, then a sub-surface barrier was considered in the model.

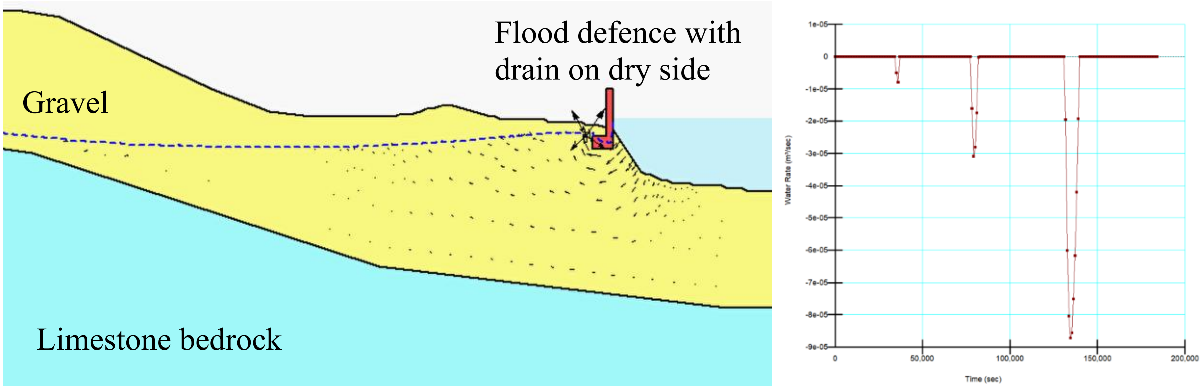

Figure 3: *Groundwater seepage model and flow to drain*

MODELLING COMPLEX HYDROGEOLOGICAL SCENARIOS

2D seepage analysis is useful where the driving head of water is a river or estuary and the focus of the seepage analysis is on the groundwater seepage beneath a flood defence close to the surface water body. However, in scenarios where the groundwater flooding is not close to a surface water body the 2D seepage analysis may not be able to adequately capture and assess the groundwater flooding. This has been observed during the seepage analysis for an area of the Midleton FRS and highlights that the type of groundwater flooding is key to informing the direction of analysis undertaken.

In Midleton there have been two major recent flooding events, Storm Frank in December 2015 and Storm Babet in October 2023. During Storm Frank the two areas worst affected in County Cork were Midleton and Bandon with flooding to a significant number of properties. Midleton has historically flooded from both extreme tides and high river flows. Some of the flood mechanisms that arose during Storm Frank were representative of past events and were predictable by reference to past studies such as the Office of Public Works (OPW) Preliminary Flood Risk Assessment mapping and the Lee Catchment Flood Risk Assessment Management (CFRAM) flood maps. However, the significant flooding that arose in Midleton Rugby Club and Lauriston housing estate during Storm Frank had not previously occurred and was not predicted in either the PFRA or Lee CFRAMS.

Storm Babet was a major low pressure weather system that impacted the southeast of Ireland on the 17th and 18th of October 2023. Significant amounts of rain fell on Midleton over the course of the storm (116mm), with a peak intensity of 12.2mm/hr.

In December 2015 prior to Storm Frank there were 29 wet days (rainfall of greater than 1mm) recorded and a total of 350mm of rainfall at the Cloyne Met Eireann weather station. Prior to Storm Babet there were fewer consecutive wet days and cumulatively less rainfall. This meant that the catchment was already saturated before Storm Frank hit resulting in a significant increase in groundwater levels and land runoff during the storm. Groundwater levels were likely lower prior to Storm Babet resulting in less groundwater induced flooding.

The spatial distribution of the rainfall may also have had an influence on the different responses between the two flood events. The groundwater flooding at Lauriston is driven from the Dungourney River catchment, whereas the fluvial flooding within Midleton town centre is primarily driven by the Owennacurra River catchment, see *Figure 4*.

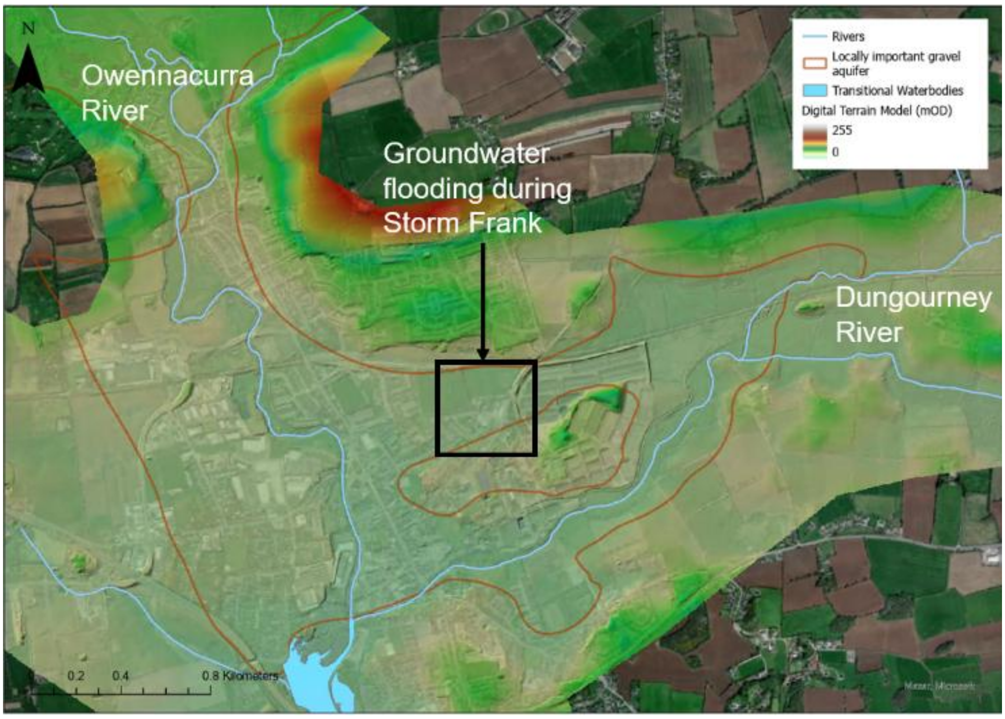

Figure 4: *Location of groundwater flooding in Midleton during Storm Frank and the ground elevation (DTM) and GSI mapped gravel aquifer*

While many areas in Midleton flooded in both storms, during Storm Frank there was an area south of Midleton Rugby Club where flooding inundated a housing estate (Lauriston) and commercial premises. This area is not close to any surface water body and the cause of the flooding is attributed to groundwater. Initially a 2D Seepage model was developed in this area but found not to adequately capture the complexity of the situation.

The rugby club and Lauriston area is a topographic low, underlain by gravels and bounded to the north and south by areas of glacial till, higher elevation and shallow bedrock, see *Figure 4*. The gravel feature is likely a palaeochannel for the original pathway of the Dungourney River. This gravel layer continues until it links up with the gravel lying beneath the Owennacurra River to the west. Groundwater flows from east to west along the gravel palaeochannel but the outflow is restricted in the Lauriston area due to the presence of a saddle in the landscape resulting in flooding at surface.

Attempted calibration of a 2D model did not yield realistic results. As the 2D model could not capture the groundwater regime in the area sufficiently to explore flood defence measures it has been decided that a 3D model is required. This work is currently in progress.

CONCLUSION

The increasing frequency of significant flooding events across Ireland underscores the necessity for robust flood defence schemes, particularly in urban areas where groundwater flooding poses unique challenges. Groundwater modelling is instrumental in identify locations at risk of seepage under flood defences and evaluates appropriate mitigation measures. The complexity of flooding scenarios requires adaptable and comprehensive modelling approaches. While 2D modelling can be suitable for proposed flood defence measures located adjacent to surface water bodies that provide the driving head, it may not adequately capture the complexity of systems where groundwater seepage occurs away from surface water bodies. In such cases, as demonstrated in the Midleton FRS, a 3D model may be required. This highlights the importance of tailoring the modelling approach to the specific hydrogeological setting and flooding challenge.

ACKNOWLEDGEMENTS

I would like to acknowledge my colleagues in Arup, particularly Gerry Baker and Shreyas, Ramesh as this groundwater modelling work is very much a team effort.

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UNDERSTANDING AND PREDICTING GROUNDWATER FLOODING IN CORK CITY

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ABSTRACT

Flooding in Cork City has become more frequent in recent decades due to its low-lying location, tidal influences, and complex underground geology. While surface flooding has been extensively studied, the role of groundwater flooding—particularly its response to changes in tidal and river levels—has received less attention. This research uses a combination of numerical modelling, transfer function regression, and machine learning to predict groundwater behaviour and dynamics.

The models demonstrate a strong correlation between river and groundwater levels, with an accuracy of up to 99% in some cases. Notably, machine learning outperformed traditional models for well-specific predictions. Findings indicate that groundwater levels frequently rise to approximately 70% of river levels, particularly in areas with buried channels or perched aquifers, rendering the city susceptible to subsurface flooding.

As sea levels rise due to climate change, the risk of groundwater flooding is expected to increase, posing a threat to infrastructure, transportation systems, and future urban development. The study emphasises that controlling river levels is crucial for reducing the risks of surface and underground flooding.

Keywords: *Groundwater Flooding, Numerical Modelling, Tidal Groundwater Interactions, Machine Learning, Coastal Groundwater Dynamics, Climate Change*

INTRODUCTION

Coastal and estuarine zones are the most stunning locations due to their ecological significance, economic value, and impact on communities. However, they are becoming increasingly vulnerable to flooding due to climate change, particularly as sea levels rise and extreme weather events intensify (Patsch & Reineman, 2024). Combined flooding in coastal cities happens when high tides, storm surges filled with water, or heavy rainfall raises water levels, overwhelming rivers and low-lying areas (Xu et al., 2023). Due to urbanisation, the old drainage system worsens the problem.

One neglected but significant part of this risk—groundwater flooding—occurs when rising water tables reach the surface due to various reasons, such as the strong hydraulic connection between the river and the aquifer, where any increase in river levels will lead to a rise in groundwater, or due to high infiltration rates in rural areas. This flooding is now recognised under the EU Floods Directive as an issue in Europe. However, it remains largely unexplored, particularly regarding how tides might affect it and what occurs underground.

The sea level significantly influences groundwater, particularly in coastal areas, where even a slight rise can substantially increase groundwater levels (Ramesh et al., 2023). Studies from around the world, including those from India, California, and Denmark, demonstrate how tides and subsurface geology influence the response of groundwater levels to sea-level changes (Su et al., 2022; Rahimi et al., 2020). Factors such as the permeability of aquifers, hidden channels, or layers on which they are built—and then subsequently buried underground—all play a significant role in controlling groundwater behaviour and dynamics.

Flooding has a long history in Cork City, with over 300 major flood events recorded since the 1800s (Jeffers, 2014). The city's location, complex geology, and growing infrastructure challenges put it at significant risk of groundwater flooding. Understanding groundwater behaviour becomes crucial as urban development.

This study fills a significant knowledge gap by examining the impact of river and tidal fluctuations on groundwater levels in the Cork area, utilising both numerical and statistical models. These tools aim to support climate-resilient infrastructure and more innovative flood planning in coastal urban settings.

METHODOLOGY

Cork City Centre is a low-lying, flood-prone urban area located at the estuary of the River Lee in southwest Ireland. The city is built on an island between two river channels and lies within a dynamic tidal estuary, subject to tidal ranges of 3–4 meters (Allen, 2007). Beneath the city lies a complex hydrogeological system composed of highly permeable glaciofluvial gravels, estuarine silts, and layers of artificial fill (Beese, 2019). These underground layers form confined and unconfined aquifers that are hydraulically connected to the river, making groundwater levels highly responsive to tides and rainfall (ARUP, 2017).

Figure 5: *Study Area – Cork City Centre*

Six monitoring wells were installed across the city to assess groundwater flooding risks and capture data on water levels. These wells represent different hydrogeological zones and distances from the river. Data from these wells—along with rainfall, river levels, and tide information—was collected and analysed to understand the interactions between groundwater and surface water.

Table 2: *Monitoring Observation Wells in Cork City Centre (Figure 1)*

Well	Location	Ground Elevation (m OD)	Depth (m)	Distance from River North Channel (m)
1	St Patrick’s Quay	2.69	7.85	7
2	Oliver Plunkett Street	2.64	8.35	136
3	Morison’s Quay	2.17	9.75	312
4	George’s Quay	2.02	8.35	557
5	Bishop Lucey Park	3.51	9.12	385
6	The Mercy Hospital	2.92	8.16	9

The research used a multi-method approach:

1. Fast Fourier Transform (FFT): Identified the dominant tidal cycles in groundwater and river data, revealing the extent of tidal influence on subsurface water levels.
2. Tidal Efficiency and Time Lag Analysis: Assessed the efficiency of groundwater in reflecting river level changes and the speed at which these changes occur at various locations.
3. Transfer Function Models (TFM): Used time-lagged river levels to predict groundwater behaviour statistically.
4. Machine Learning (Decision Tree Regression): Captured complex, non-linear relationships between river levels and groundwater responses at each well.
5. Numerical Modelling (FEFLOW): Simulated 3D groundwater flow using detailed geological data and boundary conditions to assess how tides and river levels affect groundwater on a city-wide scale.

These models were evaluated using standard statistical metrics, including RMSE, MAE, and R^2, to compare their accuracy and reliability. The combined use of physical simulations, statistical analysis, and AI-based models provided a robust framework for predicting and understanding groundwater.

RESULTS AND DISCUSSION

The groundwater data analysis from six monitoring wells across Cork City revealed a strong and consistent relationship between groundwater levels and river tides (Figure 2). Groundwater levels rise and fall with the tide, with observed delays that vary depending on the location and subsurface geology. The observed tidal cycle, approximately every 12.4 hours, identified through Fast Fourier Transform (FFT) analysis, highlighted the influence of semidiurnal coastal tides on river and groundwater levels, confirming a significant tidal signal throughout the aquifer system.

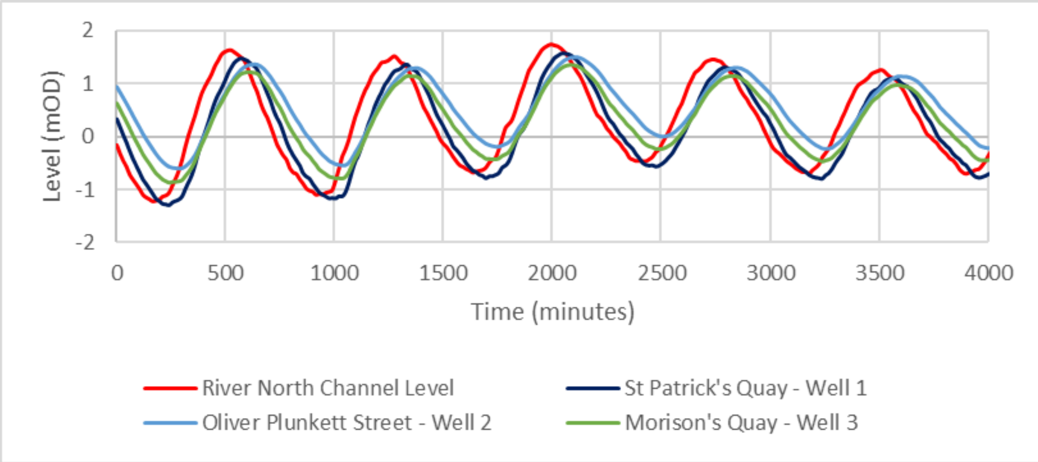

Figure 6: *River and Groundwater Levels in Wells 1, 2 and 3*

Groundwater-River Interactions

Each of the six wells demonstrated a unique response to tidal forcing, characterised by two key metrics:

- Tidal Efficiency (TE): The ratio of the amplitude of the tidal fluctuation in the groundwater to the amplitude of the tidal fluctuation in the river or ocean.
- Time Lag: The delay between river fluctuations and groundwater response.

Wells 1 and 6, despite being close to the river, had moderate lags (60–75 minutes), which were attributed to their position in unconfined aquifer zones where the water table reacts more gradually to external pressure changes. Well 2, also near the river, showed a longer lag (105 minutes) than expected, likely due to local heterogeneities in lithology, such as fine-grained sediments or buried low-permeability zones.

Well 4 shows a very strong and fast connection to the river, even though it is the farthest well from it. The water level in the well responds to tidal changes almost immediately, with a delay of only five minutes and a high tidal efficiency of 0.97. Cork City Centre was built on reclaimed land, including old canals and waterways, and features active sections (Beese, 2019). The discovery of an active culvert beneath Grand Parade in 2005 highlights the impact of past urbanisation on subsurface flow (corkpastandpresent.ie). This can explain the fast response, as these channels connect the river to the groundwater.

In contrast, Well 5 exhibited the lowest tidal efficiency (0.60) and the most extended lag (110 minutes), likely due to the formation of a thick estuarine mud that created a perched aquifer (Beese, 2019). These fine-grained sediments act as a barrier, slowing the transmission of pressure and isolating groundwater movement from immediate tidal influence. Despite this, groundwater levels in Well 5 occasionally exceeded those of the river, implying recharge or confined water buildup.

These variations highlight the influence of subsurface complexity, including fill materials, aquitards, buried channels, and anthropogenic structures, on the groundwater behaviour of Cork's aquifer.

Transfer Function Model (TFM)

The Transfer Function Lagged Regression model used river level data with various time lags to predict groundwater levels across the wells. The model achieved high predictive accuracy, with R^2 values exceeding 0.97 in all wells and low mean squared errors (e.g., 0.0042 in Well

6). Each well showed the strongest model response at its respective time lag, confirming that lagged river levels are reliable predictors of groundwater behaviour. For example:

- Well 2 had the highest coefficient at t-105 (1.0674).
- Well 4 had immediate response coefficients at t-0 (0.516).
- Well 5 responded most at t-105, reinforcing its delayed interaction.

These results confirmed that aquifer response is site-specific and well-modelled through time-dependent statistical relationships.

Machine Learning (Decision Tree Regression - DTR)

The machine learning model effectively captured non-linear dependencies and offered high-resolution, time-series predictions. Key results include:

- Highest accuracy: Well 6 (R^2 = 0.9982, RMSE = 0.0442).
- Lowest accuracy: Well 5 (R^2 = 0.903, RMSE = 0.1652).

The model's performance was generally strongest where hydraulic responses were rapid and well-defined (e.g., Wells 4 and 6) and weakest where subsurface conditions were more complex, such as in Well 5.

The narrow confidence intervals in wells like Well 6 signified stable, low-uncertainty predictions. In contrast, the wide intervals in Well 5 indicated higher variance and possible influence from additional, unmeasured factors, such as perched layers or man-made drainage networks.

Numerical Modelling (FEFLOW)

The numerical model simulated three-dimensional groundwater flow, providing spatial insights into Cork's subsurface dynamics. Model performance varied by location:

- Best fit: Well 2 (R^2 = 0.99, RMSE = 0.0735).
- Weakest fit: Well 5 (R^2 = 0.692, RMSE = 0.2871).

The model tended to overestimate groundwater levels in some wells and underestimate in others, indicating the need for further refinement, especially in zones with high heterogeneity. The confidence intervals reflected the trends observed in machine learning; Wells 5 and 4 had the widest intervals, indicating more significant uncertainty.

CONCLUSION

This study provides a comprehensive assessment of groundwater flooding in Cork City, highlighting the critical role of the River Lee's tidal and fluvial dynamics in influencing subsurface water levels. The research confirms a strong hydraulic link between river levels and the city's groundwater system through continuous monitoring and applying multiple predictive models, including numerical simulation, transfer function regression, and machine learning.

Among the approaches used, machine learning provided fast, well-level-specific predictions. At the same time, numerical modelling enabled broader analysis and a deeper understanding of groundwater behaviour in the Cork City Centre. The transfer function models were beneficial for real-time estimation of groundwater levels based on river fluctuations.

The models and the analysis of groundwater data collected demonstrated that groundwater levels generally rise to at least 70% of river levels, particularly in areas with buried channels, perched aquifers, and high-permeability zones. As climate change accelerates sea-level rise and increases storm intensity, this connection will further elevate groundwater tables, intensifying flood risks to Cork's infrastructure, roads, and buildings.

The study emphasises that managing river levels—through upstream storage, dam capacity, and tidal barriers—is crucial for preventing surface flooding and mitigating risks of groundwater inundation. Failing to consider groundwater flooding could undermine the effectiveness of surface-focused strategies.

In summary, groundwater flooding is a significant yet often overlooked contributor to urban flooding. As climate pressures intensify, integrating groundwater science into urban flood management will help protect existing infrastructure and facilitate future development.

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GROUNDWATER FLOODING AT LOUGH FUNSHINAGH, CO. ROSCOMMON: ADDRESSING THE KNOWLEDGE GAPS

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ABSTRACT

Lough Funshinagh is an intermittent turlough in South County Roscommon. It is underlain by Carboniferous limestone and, although being designated as a turlough due to its characteristic groundwater-driven water level fluctuations, it is extremely slow to drain and seldomly empties completely. The last emptying event is known to have occurred in 2004. While the nature of groundwater-surface water interaction at the turlough is uncertain, it is known to be fed by a series of surface streams and drains, many originating from groundwater sources a few kilometres to the West and North-West. The only known outlet is a swallow hole in the South-East corner which has been traced to a series of springs on the Cross River, 5km to the South. Due to its relatively unique hydrogeology, and consequent rare ecology, the turlough is of significant ecological importance and has been designated as a Special Area of Conservation under the E.U. Habitats Directive.

The slow response of Funshinagh means that, unlike other turloughs in Ireland, it does not get the opportunity to reset its flood pattern each year. This leaves it particularly vulnerable to weather events as their impacts can carry over from one year to the next. This vulnerability has been evident recently as increased rainfall over the last decade has caused Lough Funshinagh to experience unusually high flood levels. In 2016 the turlough reached a level considered to be the highest in living memory and since then it has remained relatively high, reaching further record levels in 2021 and 2024 (69.38 mAOD).

These prolonged extreme flood levels have caused significant damage and distress to the local community and flood relief efforts have been ongoing for many years. Work is underway to implement a permanent flood solution and as of April 2025 an interim flood solution has commenced whereby water is being pumped out of the Lough and discharged over 2km away into the Cross River.

These flood alleviation works have been informed by the monitoring, modelling and mapping work of Geological Survey Ireland which has been working to address the knowledge gaps regarding Lough Funshinagh since 2016. This work has enabled: 1) reconstruction of historic flood levels, 2) forecasting of potential near-future flood levels, 3) assessment of climate change impacts, and 4) assessment of flood regime alterations due to flood alleviation works. In this presentation, the methodologies and results of this work will be discussed.

SESSION V

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).

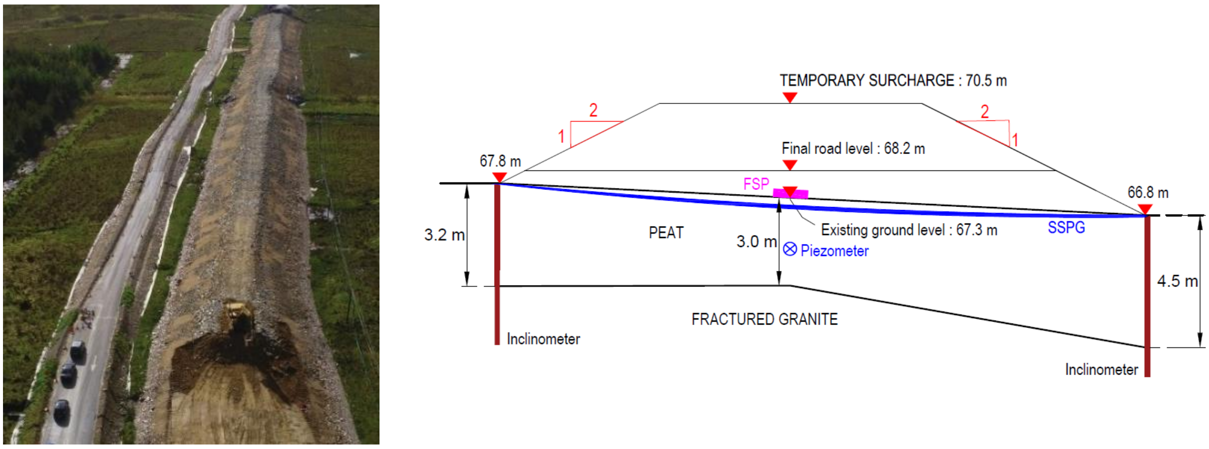

Figure 1: *(a) Surcharge removal at N56 Letterilly to Kilraine (Glenties) site, (b) Cross section at IC1 depicting embankment levels, peat thickness and instrumentation*

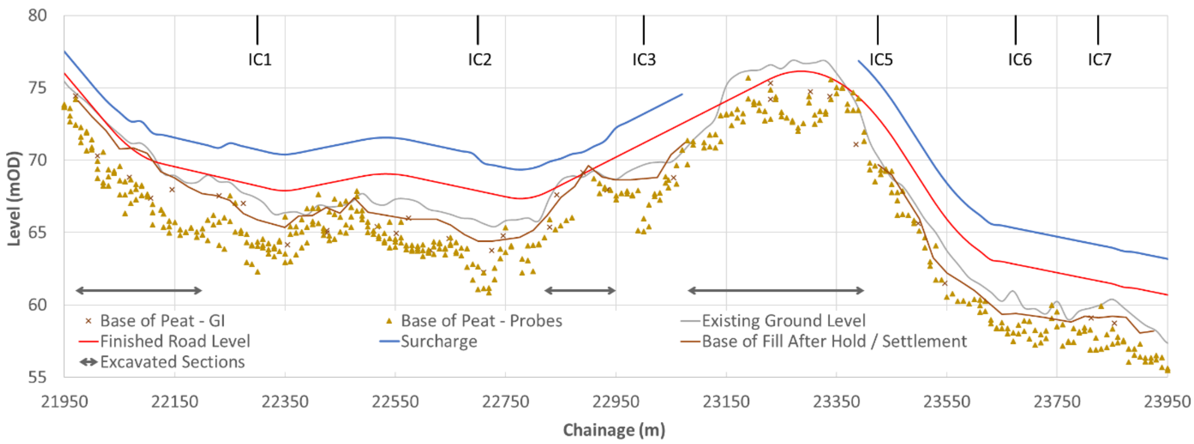

Figure 2: *Longitudinal section showing relevant levels and IC locations*

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.

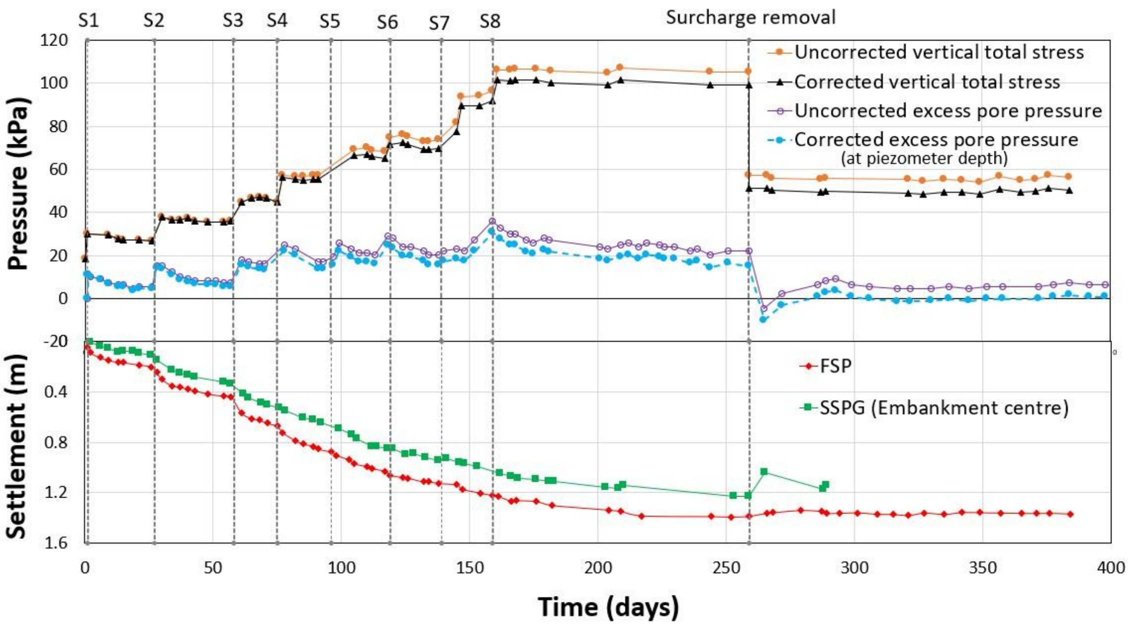

Figure 3: *Evolution of vertical total stress, excess pore pressure and settlement with time.*

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).

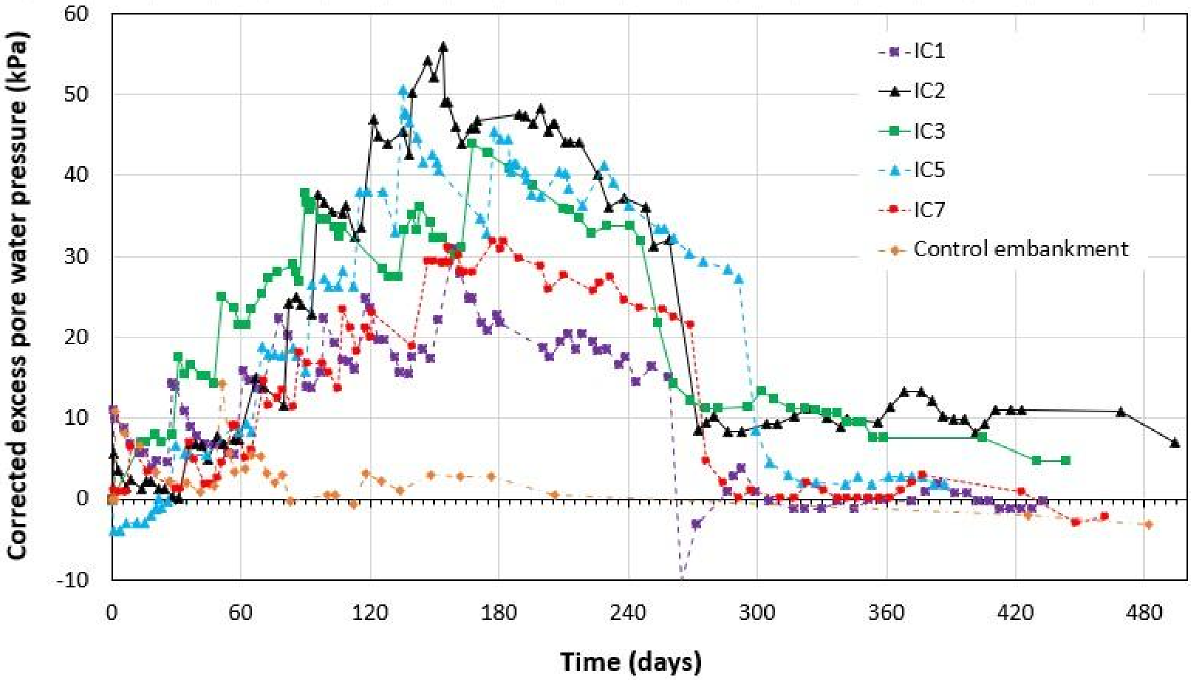

Figure 4: *Excess pore pressures at IC (mainline) and control embankment locations.*

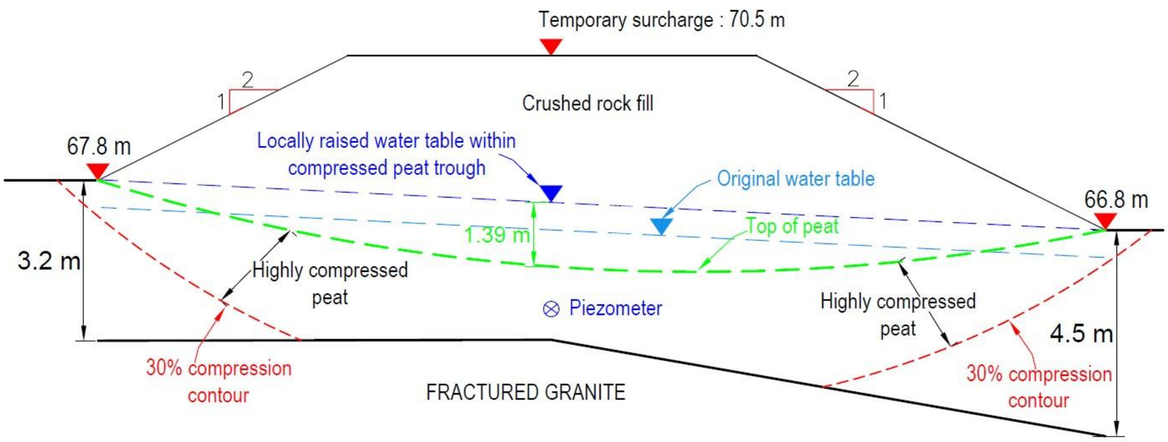

Figure 5: *Conjectured mechanism of locally raised water table within peat (IC1 shown)*

(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 2.3×10^{-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: 2.1×10^{-9}-1.1×10^{-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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REMOTE MONITORING OF GEOTECHNICAL INFRASTRUCTURE SLOPES USING SATELLITE-BASED INSAR TECHNIQUE

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ABSTRACT

Regular monitoring of geotechnical slopes is very important to prevent catastrophic failures that may lead to loss of life and property damage. Over recent years, Synthetic Aperture Radar Interferometry (InSAR) technique has emerged as a promising tool for monitoring geotechnical infrastructure slopes. This technique uses satellite images to provide cost-effective measurements without requiring physical access. This work delves into the potential and effectiveness of this technique for monitoring at the individual slope scale, as well as at a network scale. In this regard, this technique is used to monitor two-dimensional motion of a railway embankment. Results provide a detailed review of historic movements occurring between 2017–2022. Vertical displacements were identified in the railway embankment with a maximum of −23.1 mm/year for the period 2017-2022. Moreover, horizontal movement up to -10 mm/year was observed in the westward direction and +7 mm/year in the eastern direction. This study then demonstrates that how this technique can be effectively used at a network scale. In this context, InSAR data as provided by the European Ground Motion Service (EGMS) from 2016 to 2022 is used to monitor national road and railway networks in Ireland. Notably, about 50 hotspots with high rates of vertical ground motion were detected, particularly in sections underlain by peat and lacustrine sediments, with those on peat showing a strong seasonality of ground movement that is correlated with soil moisture variations. In summary, the results showed that InSAR can be used as a promising tool for monitoring geotechnical slopes.

Key words: *Geotechnical infrastructure slopes; Displacement monitoring; InSAR; Satellite images, road and railway networks, Ireland.*

INTRODUCTION

Geotechnical infrastructure slopes, such as embankments, cuttings and dams, support transportation infrastructure including roads, railways and flood defence networks [1, 2]. They are formed from or within the ground and are vulnerable to various hazards in their surroundings, such as ground motion, landslides, and structural instability [3]. Aging infrastructure poses challenges globally, and this is being exacerbated by climate change and associated extreme weather events. In Ireland, a considerable proportion of this infrastructure, particularly railways and flood defences, was poorly constructed over 100 years ago having not been made to modern engineering standards. Subsequently extreme events, such as heavy rainfall, may ultimately lead to slope failure because of increases in porewater pressure and corresponding reductions in shear strength [4]. For instance, between 2008 and 2016, several 10s of infrastructure slope failures impacted the wider Irish Rail network in association with rainfall events [5]. However, slope failure is not the only concern. Serviceability associated with seasonal (shrink-swell) movements is also a big problem, particularly in Ireland (peatlands). Extreme wet weather and unusually hot and dry conditions can lead to shrinkage and swelling of earthwork fill materials, resulting in considerable service disruption. Transportation line closures and service disruptions can significantly impact quality of life, for instance by increasing commuting times for road and rail passengers. Therefore, regular monitoring of geotechnical slopes is very important to identify problem areas and mitigate the risks of failure. A promising approach for monitoring geo-infrastructure slopes is offered by Synthetic Aperture Radar Interferometry (InSAR). Thanks to the high accuracy, high spatial coverage, and a short revisit time, this technique has the potential to provide a cost-effective and near real-time ground motion monitoring over wide areas. The technique can monitor at any time of day and is not affected by cloud cover [18]. Furthermore, a historical archive of satellite images can be used retrospectively by this technique to reveal past displacement trends.

The main objective of this study is to assess the feasibility and effectiveness of InSAR for monitoring at the individual slope scale as well as at a network scale. In this regard, Small baseline (SB) approach implemented in Stanford Method for Persistent Scatterers (StaMPS) software [6], referred to as StaMPS-SB for simplicity, is used to monitor a railway embankment constructed on peatland. The results are compared with independent in-situ (i.e., geophysical, and geotechnical) measurements. A full description of this work is provided in [7]. InSAR data as provided by the European Ground Motion Service (EGMS) is then used to monitor linear geotechnical transportation infrastructure (national road and railway) networks in Ireland.

DATA AND METHODS

STUDY AREA 1: TUBBER RAILWAY EMBANKMENT

The studied embankment is located on the Western Railway Corridor near Tubber, Co. Galway (Figure 1a-c), between the towns of Ennis and Gort, in the Republic of Ireland (longitudes 8.876° - 8.870° W and latitudes 52.985° - 52.996° N). Originally constructed in the 19th Century and following a period of closure in the late 20th Century, the railway line at Tubber was reopened in 2011 after extensive remedial works were undertaken between 2009 and 2010. A series of boreholes were drilled in 2007 (Fig. 1a) to gather more detailed geological information, which indicated that the embankment lies directly on a thick layer of highly compressible peat.

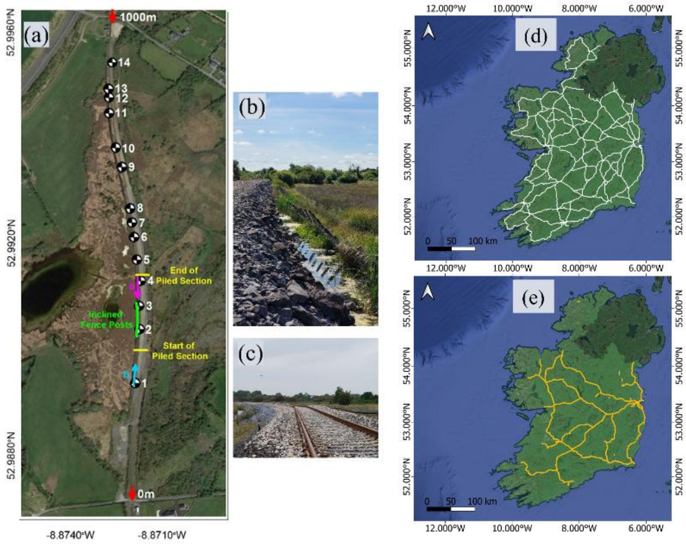

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Figure 1: *(a) satellite image showing locations of boreholes and inclined fence posts as well as arrows indicating location and orientation of photographs shown in (b), in magenta and (c) in blue. (b) Inclined fence posts along the Western side of the Tubber embankment, looking South, (c) undulating railway track along the embankment, looking North and Annotated image is from Google Earth (04/25/2021). Figure is adapted from [7]. Maps of (d) national road network including motorway, national primary, and national secondary routes, (e) active railway network in Ireland. The road and railway networks are extracted from OpenStreetMap (OSM).*

STUDY AREA 2: RAILWAY AND ROAD NETWORKS IN IRELAND

The road network of Ireland (Figure 1d) is one of the longest per capita in Europe, with a history that can be traced back to prehistoric times [8]. There are approximately 5,300 km of national roads, comprised of motorways (995 km), national primary (1,637 km) and national secondary (2,659 km) routes. The Irish rail network (Figure 1e) extends to over 1700 km of active tracks and encompasses over 3500 earthwork assets, including cuttings and embankments of varied length [5]. The rail network was largely constructed in the 1800s where most of the embankments were constructed using the construction practice of end-tipping locally available material, resulting in loosely packed fills with significant voids [9].

STAMPS-SB INSAR TECHNIQUE

The basic principle of InSAR is the exploitation of the phase difference of at least two complex SAR images acquired from different orbit positions and/or different times. In multi-temporal SAR interferometry (MT-InSAR), the basic principle remains the same as traditional InSAR, but it extends the analysis to exploit the phase difference across multiple SAR images acquired over time. This temporal dimension enables the detection and monitoring of ground displacements that occur gradually or intermittently over extended periods.

The StaMPS is an open-source software package widely used for processing and analyzing multi-temporal SAR interferometric data. The software includes PSInSAR and SB approaches [6], which both rely on identifying pixels with consistent scattering properties over time. In this study, the StaMPS-SB approach (fully discussed in [6]) was used to monitor the Tubber railway embankment.

EGMS-INSAR DATA

The EGMS is the first ground motion service of the continental scale providing information for ground displacement analysis over all Europe, with some exceptions like Switzerland and a few Balkan countries [10-12]. The service provides an annual update of InSAR velocity and displacement information. The data are processed based on the multi-temporal interferometric analysis of ascending and descending Sentinel-1 images at full resolution (having pixel footprint 14 by 4 m). The processed data are available from November 2022 in visualization and download at three levels of processing [13]: Level-2A (Basic): InSAR velocity and displacement information along the LoS in ascending and descending orbits with annotated geolocation and quality measures per measurement point, Level-2B (GNSS-calibrated): Displacement map with LoS absolute velocity and displacement information in ascending and descending orbits referenced to a model derived from Global Navigation Satellite Systems (GNSS) time series data across Europe, Level-3 (Ortho): Vertical and horizontal (East–West) components of velocity, completed for their time series, calculated from the Level-2B data. Ortho products are resampled to a 100 m grid. In this study, the vertical component of the ortho product is used to monitor the railway and national road networks in Ireland.

RESULTS AND DISCUSSION

In this section, the displacement results of the Tubber railway embankment will be first presented and described. Then, results of monitoring the Irish railway and national road networks will be discussed.

MONITORING TUBBER RAILWAY EMBANKMENT

In this case study, Sentinel-1A/1B images of both ascending and descending tracks, collected from 2017 to 2022, were analysed to obtain LOS displacements. By combining the ascending and descending orbits, the LOS displacements were decomposed into vertical (up-down) and horizontal (east-west) components, as shown in Figure 2a, 2b, respectively. The negative values in the vertical map (Figure 2a) indicate areas where the ground has moved towards the SAR sensor overall (subsidence), whereas the positive values show the movement away from the sensor (uplift). Notably, a segment with significant vertical displacements can be observed over the area delimited by the white rectangle in Figure 2a. The average and maximum vertical displacement rates were recorded as -21 and -23 mm/year, respectively, for the pixels within this segment. The horizontal (east-west) mean velocity map is presented in Figure 2b, which indicates either eastward (in blue) or westward (in red) displacement. The colour bar was clipped to -10 to +10 mm/year to highlight the spatial variance of horizontal movements. Based on the horizontal vector fields, the pattern of embankment slope instability is clearly recognisable. Both east-facing and west-facing slopes were visible to the Sentinel-1 LOS. In the southern parts of the railway line, the eastern shoulder of the embankment has an eastward displacement while the western shoulder has a westward displacement.

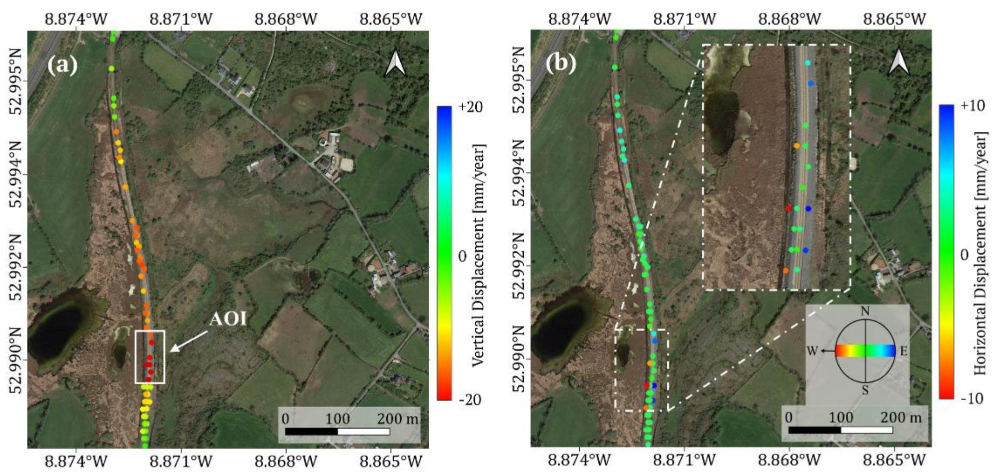

Figure 2: *(a) Vertical and (b) horizontal displacement rate maps of the Tubber embankment for the period of 2017-2022. Figure is adapted from [7].*

The results of InSAR were then compared with other geotechnical techniques (Figure 3). In this regard, a profile of vertical displacement rate along the embankment, as determined by using InSAR analysis, was compared with peat thickness profiles, records of tamping activities between 2012 and 2019, and interpretations of the depth to railway ballast base from a recent GPR profile. The section of the Tubber embankment with the greatest vertical displacement rate closely aligns with the area of the greatest embankment load, where additional rockfill was added to the embankment flanks in 2015. This section also closely corresponded to the thickest section of railway ballast, the greatest number of tamping activities and was also underlain by the deepest area of highly compressible peat.

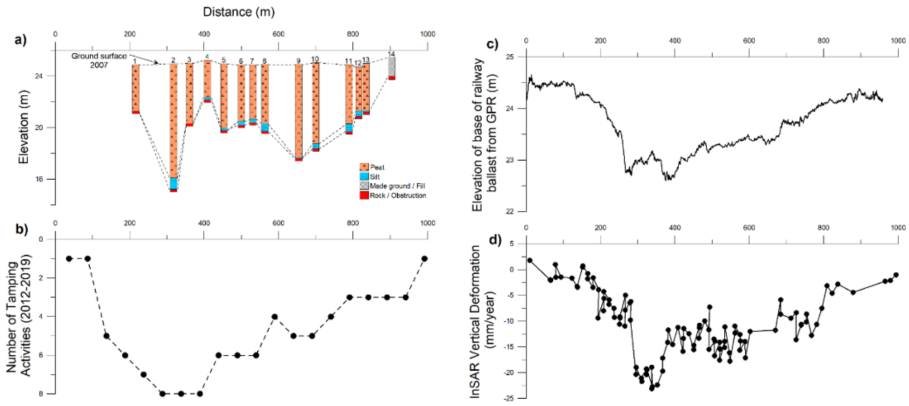

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Figure 3: *(a) profile of peat thickness, (b) number of tamping activities (2012-2019), (c) interpreted base of railway ballast from GPR, and (d) InSAR derived vertical displacement rate for the Tubber railway embankment. Figure is adapted from [7].*

MONITORING IRISH RAILWAY AND ROAD NETWORKS

The EGMS-InSAR data is used to monitor the national road and railway networks over the period from 2016 to 2022. With a 50 m buffer, a total of 37,150 points were identified along the national road network, while 13,179 points were detected along the railway network. The InSAR vertical displacement maps corresponding to these extracted points are visually represented in Figure 4.

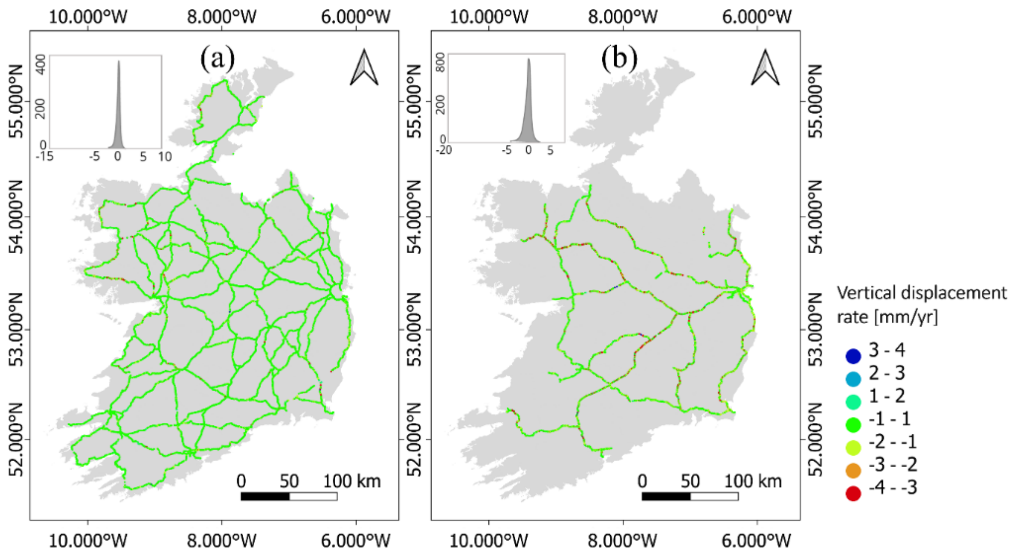

Figure 4: *Vertical velocity map from 2016 to 2022 for (a) railway and (b) national road networks. Figure is adapted from [14].*

The railway and national road networks were then categorized by considering the underlying quaternary geology. This classification facilitates our exploration of displacement outcomes within distinct geological classes. The displacement maps are analysed to categorize points into three groups: low settlement/uplift velocities (0 < velocity ≤ 5), high settlement/uplift velocities (5 < velocity ≤ 8), and very high/hotspots (8< velocity) within each geology class. The findings are summarized in Figure 5, which illustrates the percentages of points falling within these velocity ranges for each geology class along both the railway and road networks.

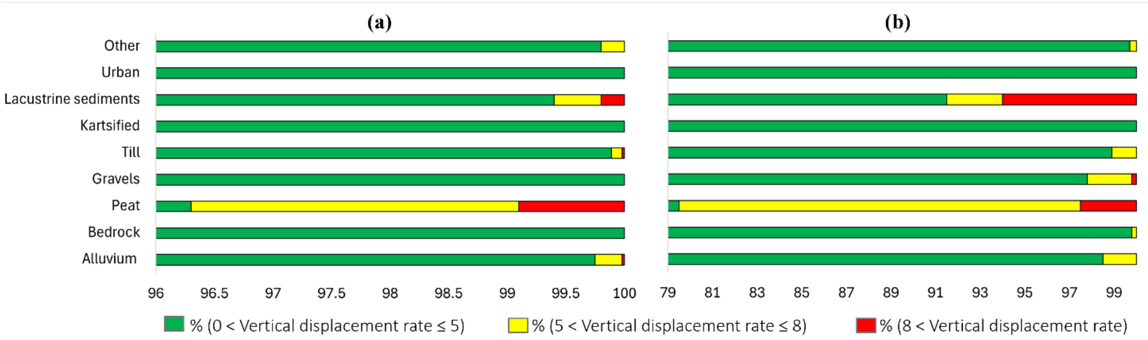

Figure 5: *Relationship between InSAR-derived ground motion rate and sediment class underlying Irish road and rail networks. (a) data for the road network (b) data for the railway network. Each bar shows the percentages of points with low (0 < rate ≤ 5), high (5 < rate ≤ 8), and very high (8 < rate) rates of settlement/uplift within a sediment (quaternary geology) class. The bedrock category indicates an absence of sediment cover. Motion rates are in mm/yr. Figure is adapted from [14].*

A comparison of the bars across the quaternary geology classes (Figure 5a, 5b) reveals that a significant percentage of points within the peat (blanket and cut over raised) class, especially over the railway network, are experiencing velocities between 5 and 8. Notably, 6% of InSAR points on the Irish rail network that lie on lacustrine sediments were detected as hotspots. This highlights that peat and lacustrine sediment classes are the most concerning quaternary categories, with respect to ground motion, over the railway network. In addition, along the road network, the peat class was identified as the most concerning class.

Along the railway network, 34 points were outside the ±8 mm/year range and hence considered as settlement and uplift hotspots. In contrast, over the national road network, 15 specific points were identified as settlement and uplift hotspots. The national road network, despite its larger dataset, has fewer hotspots compared to the railway network. This is likely due to the age of the network, as the national roads, particularly motorways, are typically of recent construction. In Figure 6, one example of hotspots over the railway network (Beagh railway embankment) is plotted. A 200 m long section of this embankment is potentially affected by subsidence up to −14 mm/year. The geological context indicates that this embankment lies on peat. Instabilities associated with peat can be due to natural processes (heavy rainfalls, alternation of dry and wet periods), as well as anthropic activities (e.g., turf cutting, land drainage, construction activities [15]. By inspecting the time series plot in Figure 6c, despite some small fluctuations, the hotspots in this region show a linear displacement trend. This suggests a long-term compression of the peat over time, contributing to the observed subsidence.

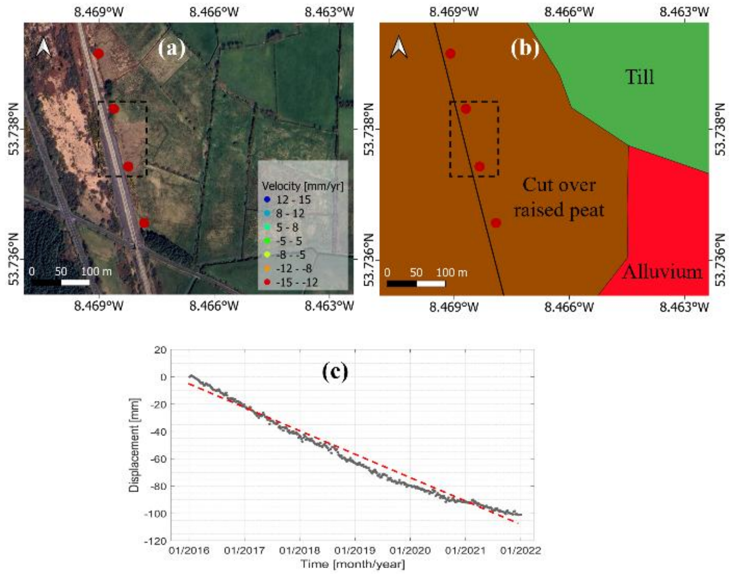

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Figure 6: *Example of settlement and uplift hotspots over railway network. (a) Displacement map, and (b) quaternary geology of Beagh railway embankment. (c) Time-series of average displacement of the pixels within the area delimited by the black rectangle. The red dotted line in (c) indicates the linear regression. Figure is adapted from [14].*

The displacement time series of InSAR measurement points within the geological were then investigated to detect hotspots with a high rate of seasonality movement (where the amplitude of the annual oscillation of the ground surface level is more than 4 mm). A total of 49 hotspots are identified over the railway network, and 94 hotspots are pinpointed over the road network. A significant proportion of points within the peat (blanket and cut over raised) and the Lacustrine sediments (including peat, silt, and clay) classes, especially over the road network, are experiencing high cyclic seasonal movements. This suggests that the main reason for cyclic behaviour in these areas is the shrinkage and swelling of underlying peat and clay, triggered by soil moisture variations during dry summers and wet winters. In the last experiment, four regions with high seasonality movement were selected over Ireland to explore potential link between InSAR-derived displacement trend and soil moisture variations. To accomplish this, the InSAR results were compared with soil moisture deficit (SMD). SMD data was obtained from Met Éireann's weather station. The selected regions and their corresponding nearest weather stations are summarized in Table 1.

Table 1: *Location of the selected seasonality movement hotspots alongside the corresponding nearest weather stations.*

Regions [Lat, Lon]	**Station name [Lat, Lon]**
Ex1 [53.95392°, -9.145375°]	Knock Airport [53.91415°, -8.811493°]
Ex2 [53.80425°, -7.858742°]	MT Dillon [53.73352°, -7.990158°]
Ex3 [54.97575°, -8.328605°]	Finner [54.49036°, -8.246032°]
Ex4 [54.06553°, -9.832982°]	Newport [53.88528°, -9.546364 °]

In Figure 7, InSAR-derived displacement trend was plotted together with SMD for the selected regions. As shown, a clear temporal correlation between displacement and SMD is evident. Wetter periods correspond to uplift, while periods of drought correspond to subsidence. For example, during the exceptionally dry summer of 2018 in Ireland, a significant drop in the displacement time series is observable. According to the geology maps, all the selected hotspots were found on peatland. Peatlands are very sensitive to changes in soil moisture and water table levels [16]. The seasonal nature of evapotranspiration and rainfall can cause cycles of soil drying and wetting, influencing both short-term seasonal variations and longer-term annual patterns in soil moisture content. These soil moisture fluctuations can result in seasonal ground movement particularly in older infrastructure potentially constructed of unsuitable fill materials or constructed on peatlands.

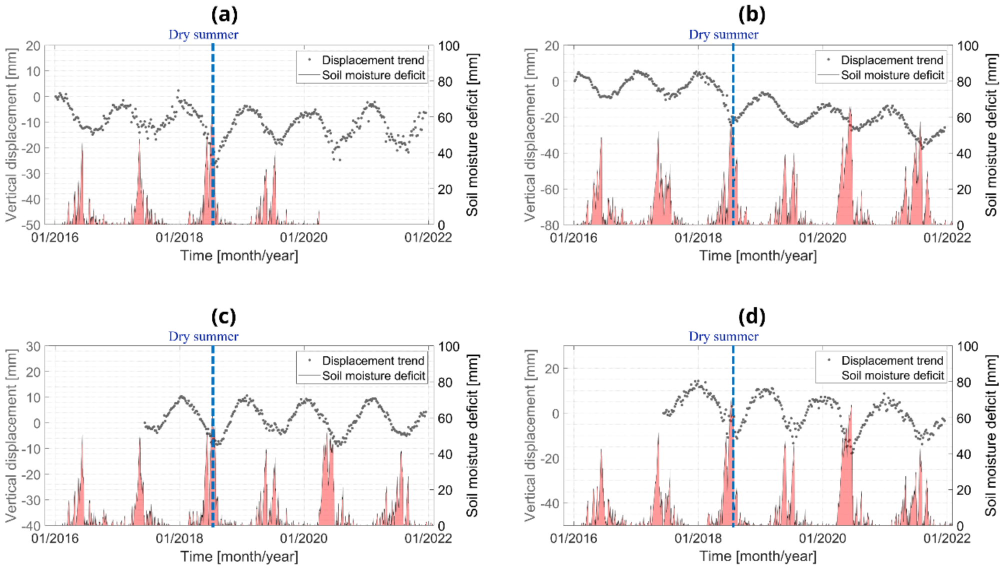

Figure 7: *Comparison of InSAR-derived displacement trend with soil moisture deficit for (a) region 1, (b) region 2, (c) region 3, and (d) region 4. Figure is adapted from [14].*

CONCLUSIONS

In this study, InSAR has been successfully utilized to monitor two-dimensional motion of a problematic railway embankment, constructed on peat. This study, which benefited from the availability of a number of different data sources, suggests that InSAR can be successful as a tool for longer term monitoring of subsidence associated with geotechnical infrastructure. The ortho product of the EGMS-InSAR data from 2016 to 2022 was also used to monitor the road and railway networks in Ireland. Several sections of Irish railway and national road networks which are experiencing significant vertical motions were discovered. Lacustrine sediments and peat classes were identified as the most concerning category, with respect to slope movements, over both the railway and road networks. Several hotspots with strong periodic fluctuations in the displacement time series were detected over the railway and road networks. Most hotspots with strong periodic fluctuations were observed over peatlands and are linked to soil moisture variations during summer and winter.

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HYDRO-GEOTECHNICAL PROPERTIES OF PEAT BUNDS USED IN THE RESTORATION OF RAISED BOGS

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POSTER ABSTRACT

Peatlands provide ecosystem services by regulating hydrology and serving as significant carbon sinks. Degradation due to artificial drainage and peat cutting has changed their natural hydrological functions, transforming peats into net carbon sources and biodiversity lacunae. However, in recent years there has been action to reverse this damage using different strategies to restore healthy wetland ecosystems. One widely used restoration technique involves the construction of peat bunds or berms to regulate water flow and facilitate rewetting of cut-away bogs. However, the effectiveness of these bunds depends on the hydro-geotechnical properties of peat, which have received few studies to date, highlighting the need for further investigation to optimize their design and long-term performance.

Here we show the hydro-geotechnical properties of peat bunds through a combination of laboratory and field testing. Falling head permeability tests and in situ slug tests were conducted to determine the saturated hydraulic conductivity. Other analysis included specific yield capacity, volumetric water content, and organic content which are critical parameters to calculate peat water retention capacity. Seepage through the bunds has been simulated using HYDRUS-2D software, whilst Plaxis-2D modelling has been used to examine consolidation through oedometer tests using a ShearScan Pro motorized system to better understand the compressibility of peat material.

Preliminary results demonstrate that peat bunds show variable hydraulic conductivity, likely due to peat heterogeneity caused by the JCB bucket compression during bund construction. This variability effects the net seepage rate through the bunds which is being included in hydraulic / hydrological models of the overall linked bund systems in order to understand the dynamics of the restoration techniques and resultant water levels in more detail. Overall, peat properties and numerical models for seepage and consolidations offers valuable insights into the hydrological performance of peat bunds in restoration projects.

DESIGN OPTIMIZATION OF LARGE-SCALE SHALLOW GEOTHERMAL SYSTEMS FOR DISTRICT HEATING AT UCD

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POSTER ABSTRACT

Borehole Heat Exchangers (BHE) in large Shallow Geothermal Energy (SGE) systems provide sustainable and low-carbon district heating solution for growing energy demand. In this study, an integrated numerical model of a Ground Source Heat Pump (GSHP) system was developed to optimize subsurface-to-surface thermal efficiency. The underground heat exchange process of BHEs was simulated using OpenGeoSys based on geological parameters from a potential development area at University College Dublin (UCD), while the surface segment employed TESPy (Thermal Engineering Systems in Python) to account for thermal demand and pipeline thermal-hydraulic balance. The system performance was evaluated through parametric analysis of BHE network, including the number, spacing, layout, and depth. Seasonal and long-term operational heat extraction patterns were further investigated to characterize system performance evolution, providing insight into quantifying thermal recharge and thermal interference effects between BHEs. An optimized design strategy for the GSHP configuration specifically tailored for the UCD potential development zone is proposed.

Keywords: *Shallow geothermal energy systems, borehole heat exchanger, OpenGeoSys, TESPy, thermal-hydraulic system optimization*

REMOTE ACTIVATION OF SALT TRACER INJECTION TO ENHANCE DISCHARGE MEASUREMENTS IN A PEATLAND CATCHMENT

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ABSTRACT

Accurate discharge measurements are essential for hydrological monitoring in peatland environments, where traditional rating curves assigned to flumes can exhibit variability across different water levels. Common tracers, such as fluorescent dyes, are often unsuitable in peatlands due to interference from high concentrations of dissolved organic matter and the unique hydrological dynamics of these ecosystems. This study presents an alternative method for measuring discharge using salt tracer dilution at four site locations within a peatland catchment. Sodium chloride tracer is injected remotely using an ISCO autosampler and downstream conductivity is continuously measured with an OTT sensor. Discharge is calculated by analysing conductivity changes, which are linked to the salt tracer concentration. This approach allows for the development of site-specific ratings for varying flow stages, improving discharge accuracy. The remote activation of the tracer injection system enables high-frequency data collection during rainfall events and fluctuating flow conditions, reducing the need for on-site monitoring and enhancing the precision of hydrological data for effective water management and restoration projects.

Key words: *Peatland, Hydrology, Blanket Bog, Sensor, Tracer*

INTRODUCTION

BACKGROUND AND CONTEXT

Peatland ecosystems are vital to the global carbon and water cycle, serving as long-term carbon stores and influencing regional hydrology. In Ireland, blanket bogs dominate upland regions, but their hydrological functioning has been altered due to anthropogenic impacts, such as drainage, peat extraction, and land-use changes. These disturbances affect runoff, water storage, and water quality, highlighting the need for accurate hydrological monitoring.

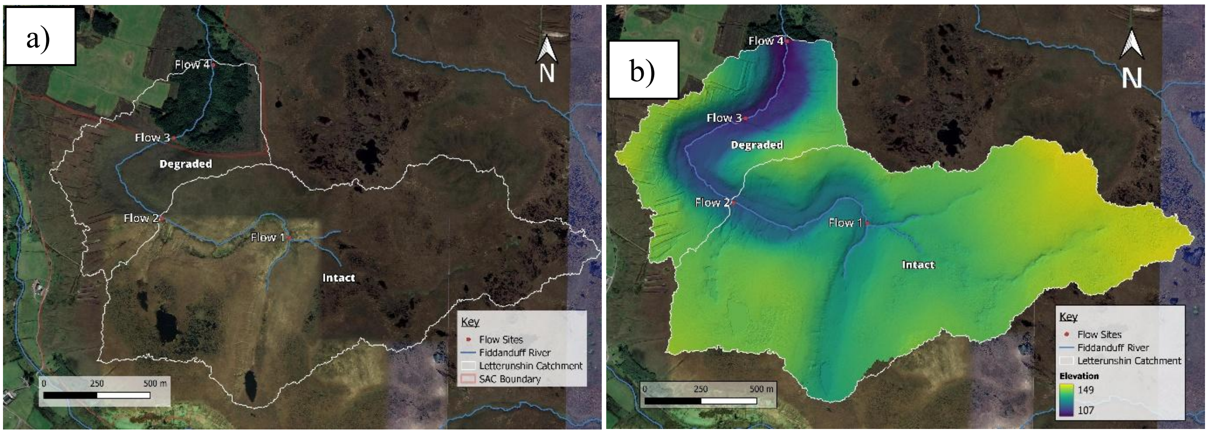
Accurate discharge measurements are fundamental to hydrological research, yet conventional methods have limitations. Flume rating equations, which relate stage height to discharge, are often derived from a limited number of point measurements, leading to inaccuracies, especially under dynamic flow conditions. These methods assume a stable stage-discharge relationship, despite natural streams exhibiting variability due to channel morphology, sediment transport, and seasonal shifts. In peatland catchments, flashy runoff and high dissolved organic matter (DOM) further complicate monitoring, often interfering with conventional tracer methods like fluorescent dyes (Bencala et al., 1983).

This study uses sodium chloride (NaCl) dilution gauging to refine rating curves for flumes in a peatland catchment. This method enables real-time monitoring of flow variability and generates higher-resolution datasets. However, while the dilution method offers advantages, potential limitations such as tracer retention in porous peat must be considered. A key innovation is the remote activation of tracer injection, which enhances data collection efficiency and researcher safety, particularly during high-flow storm events. By improving discharge measurements, this study enhances hydrological assessments and provides a scalable framework for enhanced streamflow monitoring in remote peatlands.

METHODOLOGY

STUDY AREA

This study was conducted on the Letterunshin Blanket Bog Hydrological Research Catchment (Letterunshin), located within the Ox Mountains Special Area of Conservation (SAC) in County Sligo, Ireland. The catchment comprises relatively intact upstream blanket bog and more degraded downstream areas affected by artificial drainage and the recent removal of a Sitka spruce (*Picea sitchensis*) plantation (Flynn et al, 2021). These interventions have altered the natural hydrological regime of the area, leading to changes in streamflow dynamics and water chemistry (Map 1).



***Map 1**: Map of Letterunshin Blanket Bog Hydrological Research Catchment annotated with flow measurement locations: a) Landcover map, and b) Digital elevation map.*

The Letterunshin catchment is the focus of the Sensor Application to Peatland Hydrology in Remote Environments (SAPHIRE) Project. This project enhances peatland hydrological monitoring by utilising remote sensor networks, real-time data, and telecommunications technologies. Due to its combination of relatively undisturbed blanket bog and areas impacted by artificial drainage and deforestation, this site provides an ideal setting to evaluate discharge measurement techniques and compare hydrological responses between intact and degraded peatlands.

Hydrological monitoring was conducted at four flow measurement sites (Flow 1-4) along the stream, each equipped with a trapezoidal flume. Flow 1 and 2 are located within the intact peatland while Flow 3 and 4 are in the degraded part of the catchment. While these flumes were not specifically designed for tracer mixing, their shape helps ensure uniform flow and tracer distribution. Original flume rating equations incorporated stage-dependent splits to account for varying flow conditions. A key limitation of the flume rating curves is that they were based on a limited number of point discharge measurements. This restricted dataset means that the rating curves may not fully capture variations in hydraulic conditions, particularly at higher stages where flow characteristics change. As a result, extrapolation beyond the measured range can lead to overestimation of discharge. To address these limitations, this study employs the salt tracer method, which integrates flow over time and offers a more accurate assessment of discharge dynamics in peatland streams.

SALT TRACER INJECTION SYSTEM

A remotely activated salt tracer injection system (Figure 1) was developed to address limitations in conventional discharge measurement techniques.

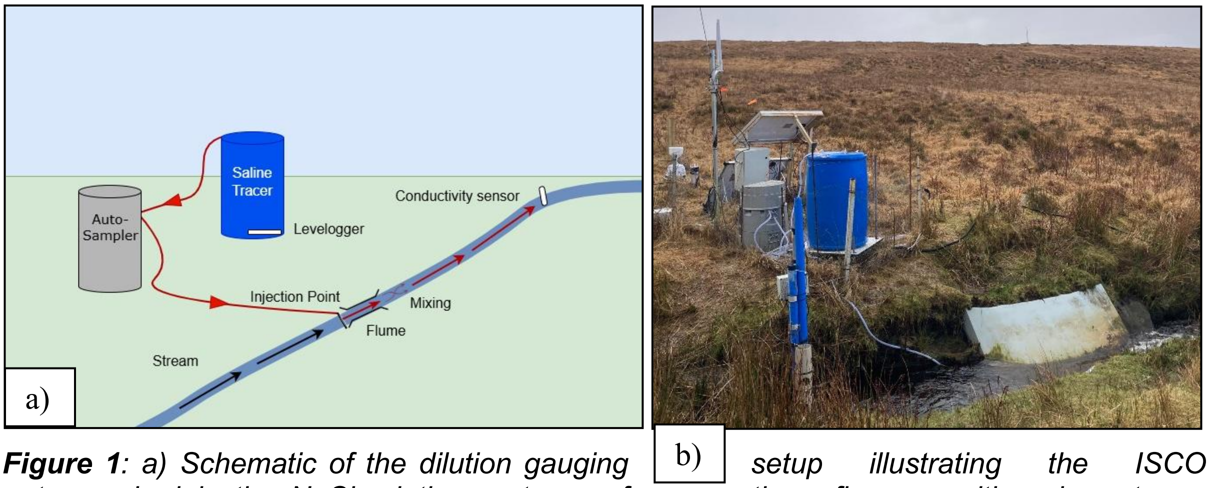


***Figure 1**: a) Schematic of the dilution gauging setup illustrating the ISCO autosampler injecting NaCl solution upstream of the flume, with downstream conductivity measurements used for discharge calculation. (b) Field setup, including the communication antenna and solar panel powering the remote activation system.*

An ISCO autosampler, typically used for water sample collection, was adapted to inject a controlled volume of NaCl solution into the stream. The autosampler was reversed to pump tracer solution from a reservoir into the stream. The saline solution was delivered through tubing connected to a perforated metal cylinder secured upstream of the flume, ensuring thorough mixing before reaching the downstream OTT conductivity sensor (~20–25 m downstream) in accordance with Day (1977).

REMOTE ACTIVATION AND PC400 INTEGRATION

The remote-controlled injection system enabled high-frequency tracer injections, particularly during storm events or variable flow conditions, without the need for manual intervention. The system was activated using Campbell Scientific's PC400 telemetry software, which allowed for real-time control of the ISCO autosampler. The autosampler was programmed to inject tracer pulses once the inhibit was lifted. The PC400 system interfaced with the dataloggers can be accessed via a Virtual Private Network (VPN) using Internet of Things (IoT) SIM cards, ensuring secure remote access.

This integration allowed for remote diagnostics, data retrieval, and system reconfiguration based on changing hydrological conditions. By leveraging this setup, tracer injections could be automatically triggered at predefined stream stage thresholds, ensuring data collection during significant flow events while reducing the need for fieldwork in hazardous conditions.

To optimise tracer injection accuracy and ensure system integrity, several precautionary measures were incorporated:

- <u>Temperature</u>: The system was programmed to prevent activation when temperatures were below freezing. While saline solutions lower the freezing point of water, the water in the tubing could still freeze, potentially impacting the tracer injection.

- <u>Air-Free Lines</u>: Before the first data collection following a reservoir refill, a pulse was performed to purge any air from the lines and ensure that the tracer solution was properly injected, thereby eliminating inaccuracies associated with air bubbles in the system.

- Tracer Concentration: A WTW conductivity sensor was used when preparing the NaCl solution concentration, ensuring it was close to the calibration standard of 50 mS/cm. This concentration level was selected as it was high enough to produce a clear breakthrough curve at high-flow conditions, which is critical for accurate discharge estimation.

- Volume Measurement: A Solinst Levelogger in the tracer reservoir monitored the volume of saline solution injected into the stream. This ensured precise calculation of the tracer volume during the injection process. This was also validated back in the lab prior to deploying the equipment.

DISCHARGE CALCULATION

Stream discharge (Q) was estimated using the tracer dilution method:

$$Q = \frac{V.C_0}{\int (C_t - C_b)dt}$$

Where:

Q *= Stream discharge (L/s)*

V *= Injected tracer volume (L), measured using the Solinst Levelogger in the tracer reservoir*

$\boldsymbol{C_0}$ *= Tracer concentration (μS/cm), validated with the WTW conductivity meter*

$\boldsymbol{C_t}$ *= Measured conductivity over time (μS/cm), recorded by the OTT conductivity sensor*

$\boldsymbol{C_b}$ *= Background conductivity (μS/cm), measured prior to tracer injection, recorded by the OTT conductivity sensor*

$\boldsymbol{\int(C_t - C_b)dt}$ *= Area under the breakthrough curve, representing the integrated conductivity signal over time*

The area under the curve is determined by integrating the difference between the measured conductivity (C_t) and the background conductivity (C_b), which provides the cumulative tracer concentration over time. Tracer dilution-based discharge estimates were compared with flume-based estimates to validate the method. The dilution gauging data was also categorised into the same stage ranges as those assigned to the flume rating equation. Additionally, direct discharge measurements were taken using a calibrated collection bin, which closely matched the dilution gauging calculations, reinforcing the accuracy of the method.

RESULTS

The comparison of discharge measurements at Flow 1 and Flow 4 highlights the tendency of the original flume equations to overestimate flow, particularly at higher stages, though the degree of overestimation varied between sites. The site-specific rating curves developed using the salt tracer dilution method provide a more accurate measure of discharge.

a) b)

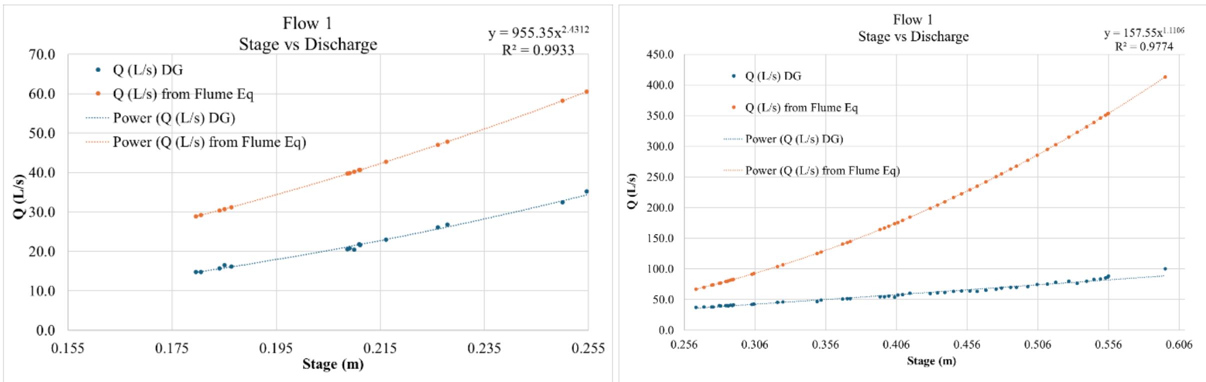


***Figure 2**: Discharge estimates at Flow 1, illustrating the stage-dependent split within the original flume rating equation. a) Shows the lower-stage relationship 0-0.255m, while b) represents higher-stage conditions 0.256-0.610m*

b)

a)

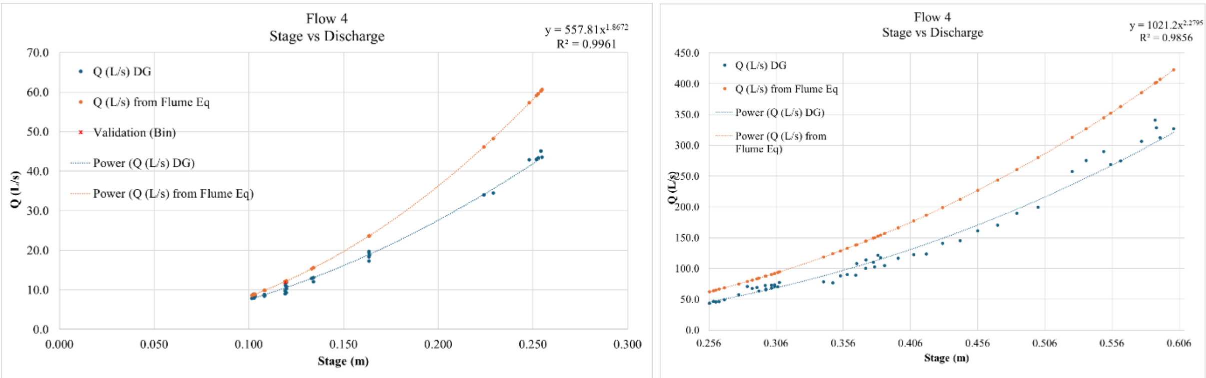


***Figure 3**: Discharge estimates at Flow 4, illustrating the stage-dependent split within the original flume rating equation. a) Shows the lower-stage relationship 0-0.255m, while b) represents higher-stage conditions 0.256-0.610m*

At both Flow 1 (intact peatland) and Flow 4 (degraded peatland), the original flume rating equations overestimated discharge, particularly at higher stages. However, the degree of overestimation varied between the two sites. At Flow 1, dilution gauging estimates deviate significantly from flume-based estimates beyond 0.255m stage height (Figure 2b). This discrepancy is likely due to site-specific hydraulic factors such as backwater effects and changing flow dynamics. In contrast, at Flow 4 (Figure 3), the flume-based estimates more closely align with dilution gauging data. This improved agreement may be attributed to the gravel stream bed which enhances turbulence and tracer mixing, improving dilution gauging accuracy. Additionally, the relatively stable channel geometry at Flow 4 minimises those backwater effects, a common issue in more peat-dominated channels.

Tracer transport dynamics may also play a role in these site-specific differences. Peat-dominated channels have greater porosity, which could cause minor tracer retention due to subsurface exchange, potentially leading to a slight underestimation of discharge. Conversely, in gravel-bed streams, enhanced mixing promotes a sharper breakthrough curve, improving discharge estimation. Further analysis is needed to quantify these effects and optimise dilution gauging applications across varying peatland conditions.

Figures 2 and 3 highlight how flume-based estimates deviate significantly at higher stages, emphasising the need for site-specific rating adjustments. Updated rating equations developed using dilution gauging data (Figure 4), provide improved discharge estimates and mitigate errors associated with flume overtopping (h > 0.61 m).

a) b)

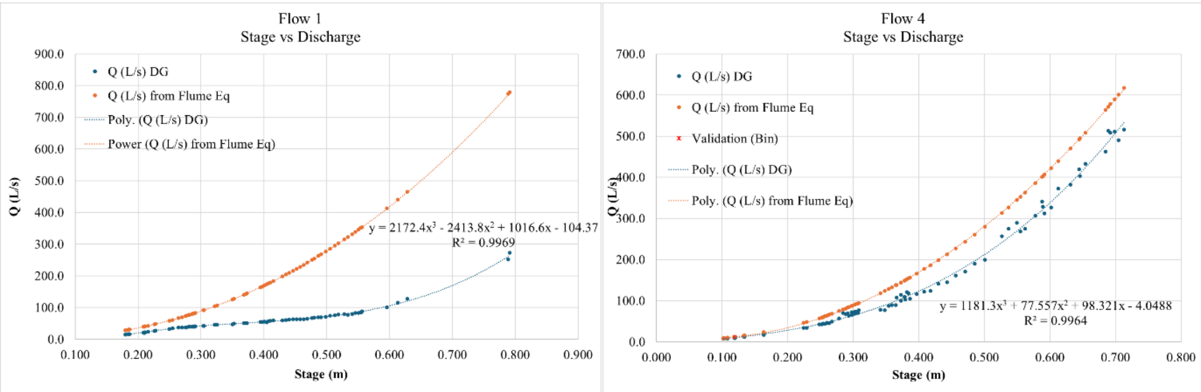


***Figure 4**: Revised site-specific rating curves for a) Flow 1 and b) Flow 4, developed using dilution gauging data*

The salt tracer method integrates flow over time rather than relying on a static stage-discharge relationship, making it particularly effective during peak flow conditions. However, its accuracy depends on proper tracer mixing and accounting for site-specific hydrological characteristics. Ongoing analysis at the remaining monitoring sites will further refine these rating curves and improve discharge assessment in peatland streams.

CONCLUSION

This study demonstrates the advantages of a remotely activated salt tracer injection system for discharge measurements in peatland catchments. Results indicate that flume-based rating equations tend to overestimate discharge, particularly under high-flow conditions, due to factors such as increased turbulence, backwater effects, and sediment transport. In contrast, the salt dilution method, enabled by remote activation, provides high-resolution, real-time discharge estimates that more accurately reflect site-specific hydrological conditions.

Differences between Flow 1 (intact peatland) and Flow 4 (degraded peatland) highlight the need to account for local hydrological variability when applying discharge measurement techniques. Future research should explore how specific catchment characteristics – such as vegetation cover, subsurface flow paths and channel morphology - influence rating curve performance across different peatland conditions. Expanding this analysis to the additional monitoring sites will help further refine site-specific rating curve accuracy.

By integrating remote telemetry with the salt tracer dilution method, this study enhances discharge measurement techniques for peatland environments, addressing key limitations of traditional flume-based approaches. Beyond improving data accuracy, this method significantly reduces the need for on-site fieldwork in hazardous conditions. As climate variability and land-use changes continue to impact peatland hydrology, scalable and adaptable monitoring solutions such as this will be essential for long-term water resource management.

ACKNOWLEDGEMENTS

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SESSION VI

DECODING COAL TAR'S HIDDEN CLUES: FORENSIC ANALYSIS OF PAHS AND ALKYLATED HOMOLOGS FOR SMARTER WASTE IDENTIFICATION AT CONTAMINATED LAND SITES

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Helder Costa, *Haley & Aldrich, Inc. USA*

ABSTRACT

Polycyclic Aromatic Hydrocarbons (PAHs) are organic compounds formed from both natural processes (e.g., forest fires, volcanic activity) and anthropogenic sources (e.g., fossil fuel combustion, industrial processes, coal tar production). Due to their persistence, toxicity, and bioaccumulation in lower organisms, PAHs are significant environmental pollutants. However, they do not bioaccumulate in most fish and higher-order organisms. Forensic analysis of PAHs is critical for accurate waste classification, particularly in identifying coal tar contamination. Coal tar, a byproduct of coal gasification, contains a distinct PAH signature, requiring differentiation from petrogenic (oil-derived) and other pyrogenic (tars and combustion-derived) sources. This study explores forensic methodologies for distinguishing coal tar's PAH profile, aligning findings with UK waste classification frameworks (WM3 and ADEPT). PAH behaviour varies by molecular weight; lower-weight PAHs (e.g., naphthalene) are more volatile and soluble, while higher-weight PAHs (e.g., benzo[a]pyrene) are more recalcitrant and bind to particulates. Alkylated PAHs, more abundant in petroleum than their unsubstituted counterparts, serve as crucial markers in differentiating petrogenic PAHs from the wide range of pyrogenic sources, including coal tar, creosote, and combustion emissions. Diagnostic ratios, such as phenanthrene/anthracene and fluoranthene/pyrene, in combination with alkylated PAH patterns, or composition, effectively distinguish petrogenic from pyrogenic PAHs. Double-ratio plots of diagnostic ratios further enhance source differentiation, revealing coal tar's signature in complex waste mixtures, which is a major challenge in classification. The use of diagnostic ratios and alkylated PAH analysis strengthens forensic evidence, ensuring proper classification under WM3 and ADEPT. By unveiling coal tar's hidden signature, this study supports regulatory decisions for hazardous waste management.

Key words: *PAHs, WM3, ADEPT, Diagnostic Ratios.*

COAL TAR

1.0 WHAT IS COAL TAR?

Coal tar is a dense, black, and viscous liquid produced as a byproduct of the pyrolysis of coal during coke manufacturing, and historically as the primary byproduct of generating gas from coal in manufactured gas plants. This process involves heating coal in the absence of oxygen at temperatures exceeding 1000°C, leading to the thermal decomposition of complex organic materials and the release of volatile compounds (Speight, 2016). The resulting products include gases, coke, and coal tar, with the latter being a highly complex mixture of thousands of organic compounds (Othmer, 2012). Coal tar is chemically distinct from bitumen, which is derived from crude oil during petroleum refining. Bitumen primarily contains asphaltenes, resins, and saturated hydrocarbons, whereas coal tar is characterized by high concentrations of aromatic hydrocarbons, including polycyclic aromatic hydrocarbons (PAHs), phenols, and heterocyclic compounds (IPCS, 2004). This fundamental difference in composition influences their physical and chemical properties, with coal tar being more thermally stable, chemically reactive, and potentially hazardous (Neff, 2010). Due to its complex composition and potential environmental impact, coal tar is regulated under various environmental and occupational health guidelines (ATSDR, 2019).

2.0 KEY COMPONENTS OF COAL TAR

Coal tar is composed of a diverse array of organic compounds, many of which are known to be toxic, persistent, and potentially carcinogenic. The primary chemical constituents include polycyclic aromatic hydrocarbons (PAHs), phenols, cresols, and benzene derivatives.

PAHs represent the most environmentally significant components of coal tar due to their toxicity, mutagenicity, and environmental persistence (WHO, 2010). PAHs are a group of organic compounds containing multiple fused benzene rings, and they are hydrophobic, meaning they have low water solubility and a tendency to accumulate in organic matter (Neff, 2010). Notable PAHs in coal tar include naphthalene, phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]pyrene, and chrysene, some of which are classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC) (IARC, 2018).

Phenolic compounds such as phenols and cresols contribute to the corrosive and toxic nature of coal tar. Coal tar also contains a variety of volatile organic compounds (VOCs), including benzene, toluene, xylene, and styrene. These compounds are known for their neurotoxic and carcinogenic effects, particularly when inhaled in high concentrations (ATSDR, 2019).

3.0 USE OF COAL TAR

Coal tar has been widely utilized in industry due to its chemical stability and high resistance to degradation. One of its primary applications is in asphalt and pavement sealing, where it is used as a sealant for driveways and parking lots to enhance weather resistance and durability (Speight, 2016). However, concerns over PAH leaching have led to bans on coal tar-based sealants in some jurisdictions (EPA, 2020). Coal tar pitch is also essential in electrode production, particularly for manufacturing carbon electrodes used in aluminium smelting and steel production, as it provides high-temperature stability and electrical conductivity (IPCS, 2004). Additionally, coal tar serves as a precursor for synthetic dyes, especially in the production of aniline dyes and other organic colorants (Neff, 2010). Another significant application is in corrosion-resistant coatings, where coal tar-based formulations are used to protect steel and concrete structures from chemical corrosion and environmental wear (Gómez et al., 2015). Additionally, coal tar has been used in dermatology for over a century due to its anti-inflammatory, antipruritic, and antifungal properties (Zhang et al., 2017). It remains an effective treatment for chronic skin conditions, including psoriasis, eczema, and seborrheic dermatitis, by helping to reduce scaling, itching, and inflammation (FDA, 2018). Coal tar-based preparations, such as ointments, shampoos, and creams, are still widely used in clinical practice despite concerns about potential carcinogenicity (IARC, 2018). Some regulatory agencies have restricted the concentration of coal tar in consumer products, requiring specific labelling and exposure guidelines (ATSDR, 2019).

4.0 POTENTIAL IMPACTS OF COAL TAR

Coal tar contamination poses significant risks to soil, water, and air quality due to its persistent organic pollutants (POPs) content. Coal tar components, particularly PAHs and phenols, have low biodegradability and strong soil adsorption, leading to long-term contamination of industrial sites (WHO, 2010). Leachate from coal tar waste can infiltrate groundwater sources, making remediation efforts challenging and costly (EPA, 2020). When coal tar enters water bodies, PAHs can bind to sediments and enter aquatic food chains. Studies have shown that PAHs in coal tar are linked to reduced fish reproductive success, increased mortality in benthic organisms, and bioaccumulation in lower trophic levels (Neff, 2010). Coal tar processing and combustion release volatile organic compounds and PAHs into the atmosphere, contributing to ground-level ozone formation, smog, and respiratory hazards (Gómez et al., 2015). Prolonged exposure has been associated with an increased risk of lung cancer, immune suppression, and cardiovascular diseases (ATSDR, 2019).

5.0 ESTABLISHMENT OF THE 16 PRIORITY POLYCYCLIC AROMATIC HYDROCARBONS (PAHS) BY THE USEPA IN 1976

In 1976, the United States Environmental Protection Agency (USEPA) established a list of 16 priority polycyclic aromatic hydrocarbons (PAHs) under the 1976 Consent Decree to address concerns about hazardous substances, particularly PAHs, and their impact on public health and the environment (EPA, 1976). The 16 PAHs (Figure 1) were selected based on criteria such as their occurrence in environmental samples, availability of analytical methods, and evidence of carcinogenicity. This selection facilitated standardized monitoring, risk assessment, and regulatory enforcement (Neff, 2010). Three PAHs, acenaphthene (Acn), naphthalene (Na), and fluorene (Fl), were included due to their detection in a drinking water contamination study, raising concerns about human exposure through ingestion (EPA, 1976). These PAHs, with moderate solubility and bioaccumulation potential, were flagged for regular monitoring in water supplies (WHO, 2010).

Seven PAHs were chosen based on the availability of reliable analytical standards, including benz[a]anthracene (BaA), benzo[a]pyrene (BaP), and others, crucial for accurate quantification and regulatory compliance (Neff, 2010; EPA, 2007). These standards enabled improved detection capabilities and data reliability (IARC, 2010). Three PAHs, anthracene (Ayl), fluoranthene (F), and phenanthrene (Pn), were included due to their listing in the 1975 EPA report on suspect carcinogens in water supplies (EPA, 1975), highlighting their carcinogenic potential based on toxicological studies (IARC, 2018).

Two PAHs, anthracene (An) and pyrene (Py), were selected for their frequent occurrence in coal tar, a byproduct of coal carbonization, often associated with contamination at industrial sites (IPCS, 2004; Neff, 2010). These compounds are persistent in the environment, accumulating in soils and sediments, posing long-term risks to ecosystems and human health (EPA, 2020). Benzo[ghi]perylene was included to represent six-ring PAHs, which are hydrophobic, resistant to microbial degradation, and persist in sediments and biological tissues (IARC, 2010; ATSDR, 2019).

Alkylated PAHs, abundant in petroleum products, were excluded due to limitations in available analytical standards (EPA, 1976). Despite their relevance for forensic analysis of oil spills, challenges in quantification led to their exclusion. Recent advancements in high-resolution mass spectrometry (HRMS) have improved their detection, prompting renewed research into their environmental impact (Speight, 2016)

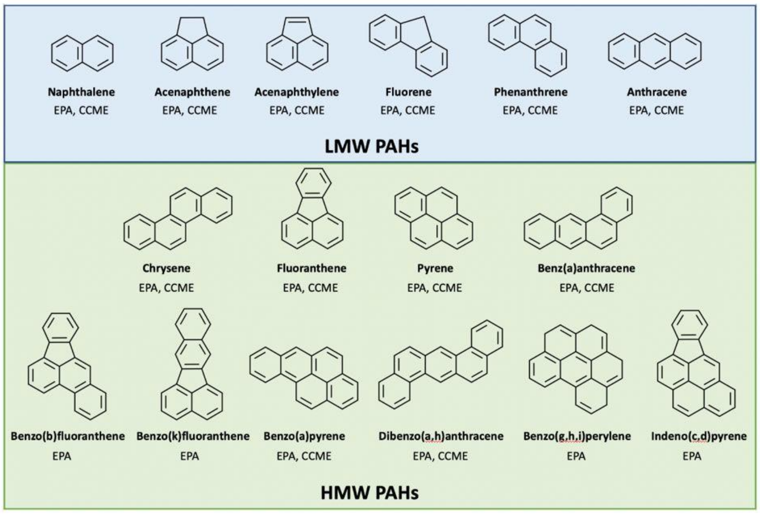

Figure 1 *16 Priority Polycyclic Aromatic Hydrocarbons (PAHs). With written permission: Dr Court Sandau, Chemistry Matters, https://chemistry-matters.com/chemicals/polycyclic-aromatic-hydrocarbons-pah/*

6.0 CLASSIFICATION OF THE 16 PRIORITY PAHS BY THE USEPA AND CCME

The 16 priority polycyclic aromatic hydrocarbons (PAHs) identified by the United States Environmental Protection Agency (USEPA) and the Canadian Council of Ministers of the Environment (CCME) are categorized into two groups: low molecular weight (LMW) PAHs and high molecular weight (HMW) PAHs (USEPA, 2002; CCME, 2010). LMW PAHs, consisting of two or three benzene rings (Figure 1), are more volatile and water-soluble than HMW PAHs. These compounds tend to be more acutely toxic but less persistent in the environment and are commonly found in petroleum products, incomplete combustion residues, and contaminated water sources (Neff, 1979). The LMW PAHs are frequently detected in drinking water contamination studies, particularly in cases of petroleum spills and industrial effluents (ATSDR, 1995). In contrast, HMW PAHs contain four or more benzene rings (Figure 1), making them less volatile and more hydrophobic. These compounds have a greater tendency to adsorb onto soil and sediments, leading to increased persistence in the environment and a higher potential for bioaccumulation.

7.0 PAH FORMATION MECHANISMS: PETROGENIC VS. PYROGENIC SOURCES

Polycyclic aromatic hydrocarbons (PAHs) originate from two primary sources: petrogenic, which is associated with petroleum and fossil fuels, and pyrogenic, which results from combustion and high-temperature processes. Differentiating between these sources is crucial for environmental forensics, as it helps in identifying contamination origins and assessing associated risks (Yunker et al., 2002).

The distinction between petrogenic and pyrogenic PAHs is primarily based on their respective compositions, or the proportions of the different PAHs and their alkylation patterns (Figure 2). Petrogenic PAHs are generally dominated by the alkylated homologues of several priority pollutant PAHs. Pyrogenic PAHs are predominantly composed of the unsubstituted priority pollutant PAHs. This differentiation provides insight into the sources of contamination and aids in regulatory compliance and remediation strategies (Tobiszewski & Namieśnik, 2012).

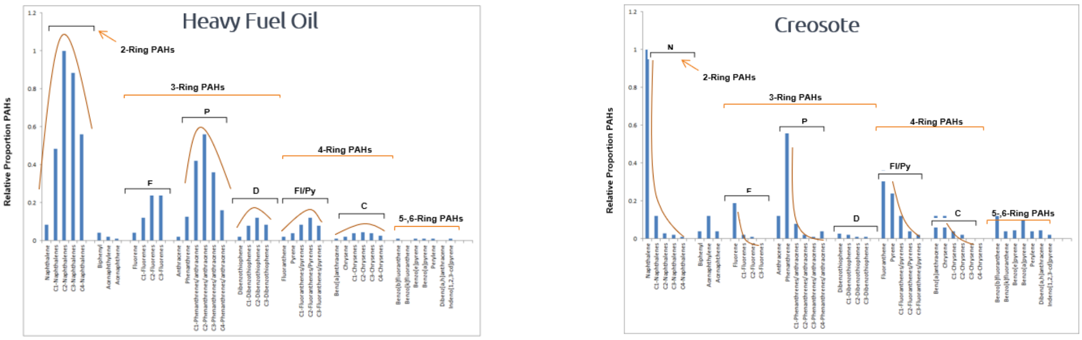

Figure 2 *Pyrogenic and petrogenic histograms showing alkylated series distributions*

7.1 Formation Pathways and the Role of PAH Diagnostic Ratios

The formation mechanisms of polycyclic aromatic hydrocarbons (PAHs) strongly influence their structural composition and diagnostic ratios. These ratios are widely used in environmental forensics to distinguish between petrogenic and pyrogenic sources, as well as to assess the extent of contamination and degradation processes (Yunker et al., 2002).

Because pyrogenic PAHs are produced under well-defined combustion conditions, the relative proportions of PAHs with similar molecular weight, volatility, and solubility remain stable, resulting in consistent diagnostic ratios. Ratios such as fluoranthene/pyrene (Fl/Py) and benzo[a]anthracene/chrysene (BaA/Chry) are commonly used to differentiate combustion-derived PAHs from those originating from petroleum sources (Figure 3). For instance, high fluoranthene-to-pyrene ratios (>0.6) are typically associated with pyrogenic origins, while very low values (<<1) suggest petrogenic input (e.g., Yunker et al., 2002; Costa and Sauer, 2005).

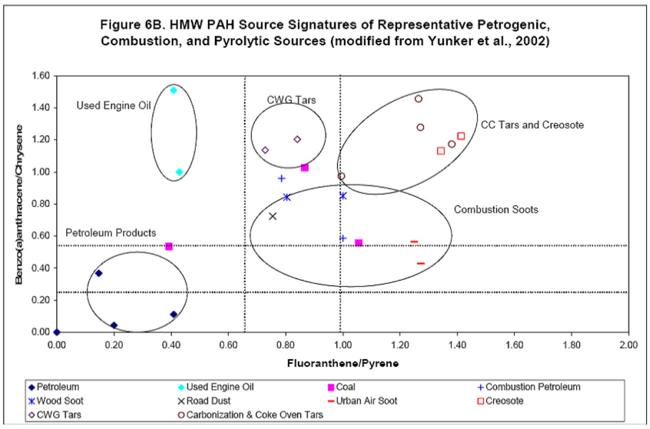

Figure 3 *Double ratio plot of benzo(a)anthracene/chrysene against fluoranthene/pyrene modified from Yunker et al. (2002)*

7.2 PAH Diagnostic Ratios for Source Identification

Diagnostic ratios of priority pollutant polycyclic aromatic hydrocarbons (PAHs) are widely applied in environmental forensics to distinguish between different types of pyrogenic (combustion-derived) sources and in some cases, also petrogenic (petroleum-derived) sources. When alkylated PAHs have also been analyzed, the relative proportions of alkylated versus unsubstituted PAHs, and the proportions of mono-, di-, tri-, and tetra-alkylated PAHs within a homologous series (e.g., alkylated naphthalenes) provide the primary distinction between pyrogenic and petrogenic sources. Diagnostic ratios of similarly stable HMW PAHs (e.g., 4-ring/4-ring, 5-ring/5-ring) provide further differentiation within the pyrogenic category to identify coal tar, creosote, or combustion residues.

Some examples of diagnostic unsubstituted PAH ratios that may differentiate pyrogenic and petrogenic PAH sources are presented in the literature. Phenanthrene/anthracene (Phe/Ant) ratio greater than 5 typically indicates a petrogenic source, while values below 5 suggest pyrogenic origins (Neff et al., 2005). Similarly, Yunker et al. (2002) suggest that an Ant/(Ant+Phe) ratio above 0.1 signifies a pyrogenic source. Other commonly referenced indicators include fluoranthene/pyrene (Flu/Py), where values greater than 1 indicate a pyrogenic source, while values below 1 suggest petrogenic contamination (Neff et al., 2005). Notably, numerous investigations of former MGP sites have demonstrated that low-temperature process tars (e.g., carbureted water gas process, oil gas tars) have Flu/Py ratios in the general range of approximately 0.6 to 1 (Jordan et al., 2021) whereas higher temperature processes (e.g., coke oven and coal carbonization processes) exhibit the higher range Flu/Py ratios referenced by Neff et al. (2005; also EPRI, 2000; Costa and Sauer, 2005). Additional HMW PAH diagnostic ratios for differentiating pyrogenic sources include indeno(1,2,3-cd)pyrene / (indeno(1,2,3-cd)pyrene + benzo(g,h,i)perylene) (IcdP / (IcdP + BghiP)), with values above 0.1 indicating combustion (Motelay-Massei et al., 2007; Yunker et al., 2002). EPRI (2000) and Costa & Sauer (2005), provide further insights into distinguishing pyrogenic tars and residues. The combined use of select HMW PAH diagnostic ratios enhances the identification of coal tar versus other pyrogenic sources such as creosote or combustion byproducts. Their robustness across different matrices makes them essential tools for forensic investigations and environmental assessments.

8.0 REGULATORY CONSIDERATIONS FOR COAL TAR IN BLACKTOP MATERIALS

The Association of Directors of Environment, Economy, Planning & Transport (ADEPT) provides clear guidance on the classification of coal tar-containing materials. As tar is classified as a Category 1 carcinogen, it must not be present at concentrations ≥0.1% (1000 mg/kg) to avoid classification as hazardous waste (ADEPT, 2020). A key indicator of coal tar “presence” under this guidance is the concentration of benzo[a]pyrene (BaP). If BaP levels reach or exceed 50 mg/kg in the blacktop alone, excluding other materials, this suggests that coal tar is present at ≥0.1%, classifying the material as hazardous. In such cases, the material must be coded under European Waste Code (EWC) 17 03 01* (bituminous mixtures containing coal tar) (DEFRA, 2010). Proper sampling and analysis are crucial for accurate classification. Any blacktop sampling must account for layer variations to ensure that different concentrations of BaP are identified. A representative sample is essential to determine the correct classification and waste disposal route (Environment Agency, 2017). Comprehensive laboratory analysis should include Speciated PAH analysis (16 priority PAHs) (US EPA, 2007) and phenols and cresols, or a phenol index >1,000 mg/kg (Environment Agency, 2017).

Furthermore, if the material is to be disposed of in a landfill, a leaching test is required to assess the potential environmental impact (BS EN 12457-2:2002).

8.1 Waste Classification and Coal Tar Contamination in Blacktop Materials

According to the Waste Classification Technical Guidance WM3, materials containing coal tar must be classified as hazardous if the concentration reaches or exceeds 0.1% (1000 mg/kg). This level triggers the hazardous property HP7 (carcinogenicity) classification (DEFRA & Environment Agency, 2015). Assessments based solely on PAHs are not compliant with legislation and cannot be used to classify waste as non-hazardous. Instead, the classification must consider the total composition of the material, including coal tar concentration and its carcinogenic potential (DEFRA & Environment Agency, 2015). A key marker for coal tar’s carcinogenicity is benzo[a]pyrene (BaP). If BaP constitutes less than 0.005% (50 mg/kg) of the total coal tar concentration, the coal tar is not considered carcinogenic and does not contribute to the HP7 classification (Environment Agency, 2017). However, where BaP concentrations in blacktop alone reach or exceed 50 mg/kg, this is a strong indicator that coal tar content is ≥0.1%, classifying the material as *hazardous waste (EWC code 17 03 01)** (DEFRA & Environment Agency, 2015).

9.0 CONCLUSIONS

Although there is some inherent complexity or "magic" to PAH source interpretation, PAH compositions follow interpretable patterns based on their source and environmental fate. If the data appear inconsistent or unexpected, this could indicate the presence of multiple sources or weathering effects that have altered the composition over time. In such cases, additional forensic tools should be applied to better characterize the contamination (Wang & Stout, 2007). An essential component of PAH forensic analysis is the inclusion of alkylated PAH homologs. The presence and relative abundance of alkylated series provide differentiation between petrogenic and pyrogenic sources. Petrogenic sources tend to have a higher proportion of alkylated PAHs due to their formation under low-temperature conditions, while pyrogenic sources feature parent PAHs in greater abundance than their alkylated homologs.

The application of stable diagnostic ratios of unsubstituted PAHs is essential for differentiating different sources of pyrogenic PAHs in environmental samples, including coal tar. Double-ratio plots of select diagnostic ratios provide a comparative framework that helps refine interpretations and increase confidence in the classification of PAH sources within a dataset (EPRI, 2000; Yunker et al., 2002; Costa and Sauer, 2005).

Finally, collaboration with the analytical laboratory is key to ensuring high-quality and interpretable PAH data. Laboratories can offer valuable insights into the methodology used, detection limits, and appropriate quality control measures. Establishing early communication with the laboratory will help tailor the analysis to meet the specific needs of the investigation and ensure that the most informative PAH data is obtained.

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NATURAL RADIONUCLIDES AS TRACERS OF RIVER-AQUIFER INTERACTIONS: A NOVEL APPROACH FOR MONITORING SURFACE WATER DYNAMICS IN IRISH RIVER SYSTEMS

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ABSTRACT

Climate change intensifies hydrological extremes, threatening freshwater ecosystems and water resource sustainability. This proposal outlines an innovative methodology to investigate groundwater-surface water interactions using natural radionuclides—Radon (^{222}Rn) and Thoron (^{220}Rn)—as environmental tracers. Focusing on Ireland's largest river system, the proposal aims to map spatiotemporal variations in groundwater discharge and solute transport to address current gaps in understanding baseflow dynamics and climate resilience. The proposed framework combines in-situ measurements (via Lucas cell-based instrumentation) and laboratory analyses of water and sediment samples to establish radon mass balance models. Seasonal field campaigns will identify preferential groundwater discharge zones, quantify exchange fluxes, and integrate findings with geospatial datasets to refine hydrological conceptual models. By coupling Radon/Thoron measurements with conventional indicators (e.g., pH, conductivity), this non-invasive, cost-effective approach avoids artificial tracer injection while offering high-resolution spatial-temporal modelling. Key anticipated contributions include 1) a replicable methodology for quantifying river-aquifer interactions, adaptable to diverse catchments. 2) high-resolution mapping of groundwater discharge patterns to inform sustainable water management. 3) deep understanding into climate-driven hydrological shifts, such as drought-flood transitions, and their impacts on water balance. As the first proposed application of dual Radon/Thoron tracing in Ireland, this methodology seeks to advance hydrological monitoring tools and highlight the importance of ecological preservation and climate adaptation. The results could empower decision-makers to prioritize groundwater-dependent ecosystems and optimize restoration strategies to align with global sustainability goals for water resource management.

Key words: *Radionuclide, environmental tracer, aquifer-ground water interaction, climate change adoption, river systems*

INTRODUCTION

Freshwater ecosystems are under increasing pressure from climate change, which exacerbates hydrological extremes such as droughts and floods. These changes threaten the sustainability of water resources and the ecological health of river systems, particularly in regions like Ireland, where rivers such as the Shannon are considered a strategic water resource which also supports biodiversity [1]. Understanding the dynamics of groundwater-surface water interactions is the first and most important step for effective water resource management, especially in the context of climate resilience. Groundwater discharge into rivers, often referred to as baseflow, sustains river flow during dry periods and contributes to the overall health of aquatic ecosystems. However, quantifying the interaction and relationship of groundwater and surface water remains a challenge due to the complexity of hydrological processes and the limitations of traditional monitoring methods [2]. Natural radionuclides, particularly Radon (^{222}Rn) and Thoron (^{220}Rn), have emerged as powerful environmental tracers for studying groundwater-surface water interactions. These isotopes are naturally produced in aquifer matrices through the radioactive decay of their parent nuclides, Radium-226 (^{226}Ra) and Radium-228 (^{228}Ra), respectively. Unlike surface waters, which typically have low concentrations of radon and thoron, groundwater exhibits significantly higher concentrations—often three to five orders of magnitude greater [3]. This stark contrast makes radon and thoron ideal tracers for identifying and quantifying groundwater discharge into rivers, lakes, and other surface water bodies [4].

The use of radon as a hydrological tracer is not entirely new; it has been successfully applied in various settings worldwide, including coastal oceans, rivers, lakes, and estuaries [5]. For instance, studies in the United States, Australia, and China (see Figure 1) have demonstrated the utility of radon in mapping groundwater discharge and understanding solute transport processes [6]. However, the application of thoron, with its shorter half-life (55.6 seconds compared to radon’s 3.8 days), is relatively novel. Thoron’s rapid decay makes it particularly useful for identifying localized and transient groundwater discharge events, especially in dynamic river systems [7]. Despite its potential, the combined use of radon and thoron as tracers has not been widely explored, particularly in Ireland, where the hydrological impacts of climate change are becoming increasingly evident [8].

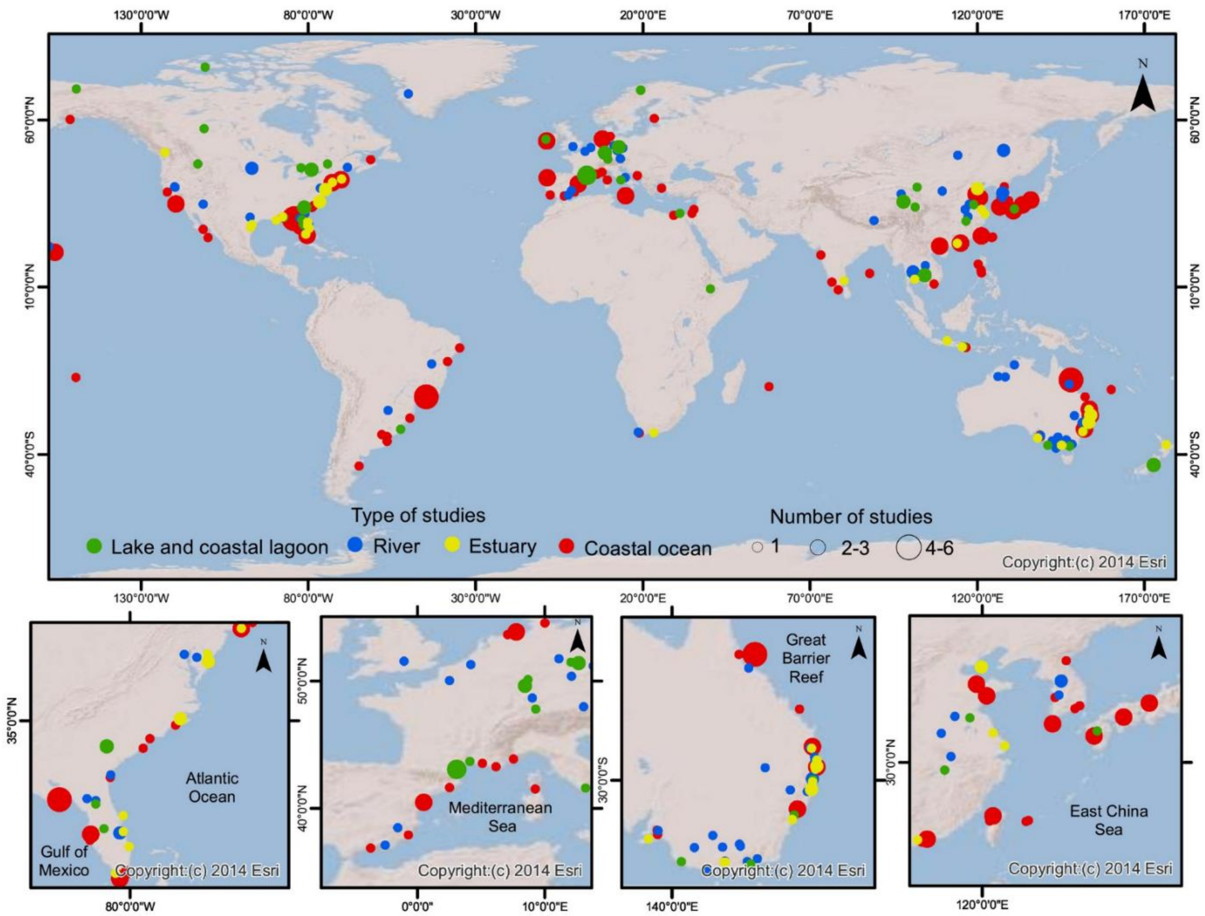

Figure 1: *Worldwide applications of radon as a hydrological tracer, map extrapolated from [1].*

This paper proposes an innovative approach to monitoring groundwater-surface water interactions in Irish river systems, with a focus on the River Shannon, Ireland’s largest river. By leveraging the unique properties of radon and thoron, this proposal aims to provide high-resolution spatial and temporal data on groundwater discharge patterns, baseflow dynamics, and solute transport. The proposed methodology combines in-situ measurements using Lucas cell-based instrumentation with laboratory analyses of water and sediment samples to establish radon mass balance models. Seasonal field campaigns will be conducted to identify preferential groundwater discharge zones, quantify exchange fluxes, and integrate findings with geospatial datasets to refine hydrological conceptual models [9].

The integration of radon and thoron measurements with conventional environmental indicators such as pH, conductivity, and temperature offers a non-invasive, cost-effective alternative to traditional tracer methods, which often require artificial tracer injection. This approach not only avoids potential ecological disturbances but also provides real-time, high-resolution insights into hydrological processes [10]. By coupling these measurements with advanced geospatial modelling techniques, the project aims to develop a replicable methodology for quantifying river-aquifer interactions, adaptable to diverse catchments and hydrological settings [11].

The anticipated contributions of this research are threefold. Firstly, it will provide a detailed understanding of groundwater discharge patterns in the River Shannon, including the spatial and temporal variability of baseflow. Secondly, it will highlight the climate-driven hydrological shifts, such as drought-flood transitions, and their impacts on water balance. Finally, the study will make recommendations for monitoring programmes and tools that can inform sustainable water management practices and support ecological preservation efforts [12]. By prioritizing groundwater-dependent ecosystems and optimizing restoration strategies, the findings of this study align with global sustainability goals for water resource management, particularly those outlined in the United Nations Sustainable Development Goals (UNSDGs) [13].

METHODOLOGY

The investigation of groundwater-surface water interactions represents a key component in understanding hydrological systems, particularly in the context of past, present and future climate change impacts on water resources. This study employs natural radionuclides—specifically radon (^{222}Rn) and thoron (^{220}Rn)—as environmental tracers to quantify and characterize river-aquifer interactions. The methodology leverages the distinct geochemical properties of these noble gas isotopes, which serve as excellent indicators of groundwater discharge into surface waters [14]. Radon and thoron possess several advantageous characteristics that make them particularly suitable for tracing groundwater-surface water interactions. As chemically inert noble gases, they remain unaffected by biogeochemical reactions that might alter the behaviour of other tracers [15]. Furthermore, the substantial concentration gradient between groundwater and surface water—typically two to three orders of magnitude higher in groundwater—provides a strong signal for detecting groundwater inputs to rivers [16]. This natural concentration difference eliminates the need for artificial tracer injection, offering a non-invasive approach to hydrological investigation that minimizes environmental impact while providing high-resolution spatial-temporal variations [17].

FIELD SAMPLING DESIGN AND PROCEDURES

The field sampling strategy will establish a seasonal campaign to capture temporal variations in groundwater-surface water dynamics across the hydrological year. Sampling locations along the Shannon River system are strategically selected based on geological characteristics, known or suspected groundwater discharge zones, and accessibility considerations. The sampling network encompasses a range of hydrological settings to provide comprehensive coverage of the river system's diverse hydrogeological conditions. Groundwater samples are collected in 250-ml glass vials after adequate purging of the sampling wells to confirm representative samples of aquifer water [18]. The purging process removes stagnant water from the well casing, allowing fresh groundwater to enter the sampling zone. Given the relatively high radon activity concentration in groundwater smaller sample volumes are sufficient for accurate measurement [19]. Samples are carefully sealed to prevent gas loss and analysed within 3-4 days of collection to minimize decay-related errors, as radon has a half-life of approximately 3.8 days.

Surface water sampling presents unique challenges due to the significantly lower radon concentrations compared to groundwater. To address this limitation, in-situ monitoring is employed using specialized equipment that can detect the low concentrations typically found in river water [20]. Sampling points are established along predetermined river reaches, with spacing determined by the expected scale of groundwater discharge features and the river's hydrological characteristics. At each sampling location, complementary parameters including electrical conductivity, pH, and water temperature are measured to provide additional context for interpreting radon data [21]. Complementary sediment samples may be taken at key locations to calibrate water measurements.

INSTRUMENTATION AND ANALYTICAL METHODS

The in-situ measurement of radon and thoron in water samples employs various techniques, with this project primarily utilizing instruments based on the Lucas cell method. The Lucas cell technique represents one of the most sensitive and reliable approaches for radon detection, offering precise and accurate measurements even at low concentrations [22]. The specific instrument employed is the RTM 1688-2 Radon and Thoron monitor, which provides real-time measurements with high sensitivity. The Lucas cell consists of a chamber coated internally with zinc sulphide activated with silver (ZnS(Ag)), which scintillates when struck by alpha particles produced during radon decay [23]. The scintillation events are detected by a photomultiplier tube and converted to electrical pulses, which are then counted to determine radon concentration. The calibration factor for the system is typically in the range of 64.7 ± 6.9 cpm/Bq/L, with detection and determination limits of approximately 0.007 and 0.020 Bq, respectively [24]. For in-situ measurements, water is circulated through a gas-water exchanger where radon partitions into an air loop according to its partition coefficient. The air is then directed to the Lucas cell for measurement. This approach allows for continuous monitoring of radon concentrations in the field, providing high-resolution temporal data [25]. While the Lucas cell method serves as the primary analytical technique, several alternative methods are available for radon measurement in water, including ionization chambers, semi-conductor detectors, gamma-ray spectrometry, and liquid scintillation counting (LSC) [26]. Each technique offers specific advantages in terms of sensitivity, sample throughput, and field applicability, with selection dependent on study objectives and logistical constraints.

RADON MASS BALANCE MODELING

The quantitative interpretation of radon data for determining groundwater discharge rates relies on mass balance modelling approaches. The project employs the FINIFLUX model, an implicit finite element model specifically designed for quantifying groundwater fluxes and hyporheic exchange in streams and rivers using radon as a tracer [27]. This model represents an advancement over previous analytical approaches, providing numerically stable estimates of groundwater fluxes and hyporheic residence times from field data.

The governing equation for the one-dimensional steady-state radon mass balance in a river can be expressed as:

$$\partial/\partial x(Qs_c) = wI(c_{gw}-c) - wdkc - wd\lambda_c + wd\theta h(\gamma - \lambda_c)(1 - e^{\wedge}(-\lambda_{th}))$$

Where x [L] is the one-dimensional stream length, w [L] is stream width, d [L] is stream depth, Qs [L³/t] is stream discharge, I [L²/t] is the rate of groundwater inflow, c and cgw [M/L³] *represent radon concentration in the stream and groundwater respectively, k [t^{-1}] is the degassing coefficient, and λ [t^{-1}] is the first-order decay constant for radon [15]. Hyporheic exchange parameters include θ (porosity of streambed sediment), h [L] (depth of hyporheic exchange), th [t] (mean residence time of water in the hyporheic zone), and γ [$M/L^3/t$] (radon production rate within the hyporheic zone).*

FINIFLUX implements this equation using an implicit numerical scheme based on finite elements, which provides superior numerical stability compared to explicit finite difference methods or inversion techniques [29]. The model discretizes the river reach into segments and iteratively solves the mass balance equation for groundwater discharge and hyporheic exchange parameters. This approach reduces non-uniqueness in parameter estimation and avoids physically impossible negative values that can arise from numerical instability in simpler methods [30].

The model is coupled with parameter optimization using Parallel-PEST to iteratively refine estimates of groundwater discharge rates and hyporheic residence times based on field measurements [31]. This optimization process involves systematic adjustment of model parameters to minimize the difference between observed and simulated radon concentrations along the river reach.

DATA INTEGRATION AND ANALYSIS

The methodology incorporates comprehensive data integration and analysis procedures to maximize the utility of radon and thoron measurements. Field data are integrated with geospatial datasets using Geographic Information Systems (GIS) to develop high-resolution maps of groundwater discharge patterns [32]. This spatial analysis enables identification of preferential discharge zones and quantification of their contribution to river baseflow. Temporal variation analysis examines seasonal patterns in groundwater-surface water interactions, with particular attention to hydrological extremes such as drought and flood conditions [33]. This temporal dimension provides precise information on the resilience of baseflow contributions under varying climatic conditions, addressing a major knowledge gap in understanding climate change impacts on river systems. The integration of radon/thoron data with conventional hydrological indicators (e.g., pH, conductivity) enhances the interpretative power of the analysis, allowing for more robust conceptual models of groundwater-surface water exchange [34]. Statistical techniques including correlation analysis, principal component analysis, and time series analysis are employed to identify relationships between radon concentrations and other environmental parameters.

VALIDATION AND QUALITY ASSURANCE

Quality assurance procedures are implemented throughout the sampling and analytical process to ensure data reliability. These include field blanks, duplicate samples, and standard reference materials to assess measurement accuracy and precision [35]. Analytical instruments undergo regular calibration using certified radon standards to maintain measurement accuracy throughout the study period. The methodology incorporates validation through comparison with conventional hydrological methods where possible, including differential gauging, seepage meters, and hydraulic gradient measurements [36]. This multi-method approach provides cross-validation of groundwater discharge estimates and strengthens confidence in the results. Uncertainty assessment is conducted through sensitivity analysis of the mass balance model, identifying the parameters that most strongly influence discharge estimates [37]. This analysis guides the allocation of resources toward reducing uncertainty in the most influential parameters, improving overall model reliability.

APPLICATIONS TO IRISH RIVER SYSTEMS

The methodology is specifically designed for application to Irish river systems, with particular focus on the Shannon River as Ireland's largest river system. The approach is adaptable to diverse catchment characteristics, including the karst-dominated landscapes common in western Ireland [38]. The non-invasive nature of radon/thoron tracing makes it particularly suitable for environmentally sensitive areas, including the numerous designated conservation areas along Irish rivers. The high-resolution spatial and temporal data generated through this methodology will inform sustainable water management practices, particularly in the context of increasing hydrological extremes due to climate change [39]. By quantifying groundwater contributions to river flow under varying conditions, the approach provides valuable information for water resource planning, ecological conservation, and climate adaptation strategies.

RESULTS, CHALLENGES AND POTENTIAL DELIVERABLES

The proposed methodology is expected to yield comprehensive understanding of the groundwater-surface water interactions in the River Shannon, with implications for hydrological science, ecosystem management, and climate adaptation. Spatially, high-resolution mapping of radon and thoron concentrations will likely reveal discrete zones of groundwater discharge, particularly in areas with permeable geological substrates (e.g., karstic limestone or alluvial deposits). For instance, regions near geological faults or fracture networks may exhibit elevated radon activities, indicating preferential pathways for groundwater influx. These findings will complement existing geospatial datasets from Ireland’s Tellus program, which maps radiometric and geochemical properties, enabling a synthesis of subsurface characteristics with surface water dynamics. Temporally, seasonal sampling campaigns are anticipated to demonstrate cyclical variations in groundwater discharge. Winter months, characterized by higher aquifer recharge due to increased precipitation, may correlate with amplified baseflow contributions to the river. Conversely, summer droughts could reduce groundwater discharge, exacerbating low-flow conditions and stressing aquatic ecosystems dependent on stable baseflow. Such temporal trends will be deterministic for predicting how climate change—specifically, intensified drought-flood cycles—might alter the River Shannon’s hydrological regime.

Quantitative outputs from the FINIFLUX model will provide baseflow estimates for the study reaches, resolving the proportion of streamflow derived from groundwater versus surface runoff. This is particularly relevant for Ireland, where baseflow sustains river ecosystems during dry periods and dilutes pollutants from agricultural and urban sources. For example, in catchments with intensive agriculture, elevated nitrate levels in groundwater could be traced to riverine inputs via radon anomalies, offering a novel tool for identifying contamination pathways. Additionally, coupling radon data with electrical conductivity (EC) and temperature measurements may disentangle the contributions of different water sources (e.g., deep groundwater vs. shallow soil water), refining conceptual models of catchment-scale water movement. Long-term, the integration of these results with climate projections from Met Éireann could reveal shifts in groundwater discharge patterns under future scenarios. For instance, increased winter rainfall may enhance aquifer recharge and baseflow, while prolonged summer droughts could diminish groundwater contributions, altering the river’s ecological balance. Such projections will inform adaptive management strategies, such as prioritizing groundwater protection in recharge zones or modifying water abstraction permits to sustain baseflow during droughts.

KEY CHALLENGES

Despite its innovative approach, the methodology faces several technical and logistical challenges. Technical limitations are foremost, particularly the short half-life of thoron (55.6 seconds), which complicates in-situ measurements. While the RTM 1688-2 monitor’s real-time capabilities mitigate this issue, rapid sample degradation during transportation or delays in analysis could still introduce errors. Furthermore, distinguishing groundwater discharge from hyporheic exchange—the movement of water through riverbed sediments—remains complex. Hyporheic flow can elevate radon activities without contributing to net groundwater discharge, necessitating advanced modelling frameworks like FINIFLUX to partition these processes. Sediment heterogeneity also poses challenges; variable ^{226}Ra and ^{228}Ra activities in riverbed materials could lead to inconsistent radon production rates, requiring gamma spectrometry validation to ensure accurate source-term calculations. Fieldwork logistics present additional hurdles. Accessing remote or ecologically sensitive reaches of the River Shannon during extreme weather (e.g., winter floods) may delay sampling campaigns or compromise data quality. For example, high turbidity during flood events could interfere with radon measurements, while frozen conditions in winter might impede sediment coring. Moreover, coordinating with multiple stakeholders—including the EPA, Geological Survey Ireland, and local landowners—requires careful planning to align sampling schedules with regulatory and environmental constraints. Data interpretation challenges include reconciling discrepancies between radon-derived discharge rates and conventional methods like EC-based mixing models or differential flow gauging. For instance, radon's sensitivity to hyporheic exchange might yield higher discharge estimates compared to EC models, which primarily reflect solute mixing. Iterative calibration and multi-tracer validation will be essential to resolve such inconsistencies and ensure robust conclusions.

TARGETED DELIVERABLES

The project's benefits span scientific, environmental, and policy domains. Scientifically, it introduces Ireland's first dual radon-thoron tracing framework, advancing the global understanding of groundwater-surface water interactions in temperate, high-rainfall catchments. By coupling in-situ measurements with geospatial modelling, the methodology generates high-resolution datasets that transcend the limitations of traditional monitoring techniques (e.g., piezometer networks), which often lack spatial granularity. This project would help to achieve the following specific deliverables:

1. Estimation of river infiltration into aquifers: radon and thoron can be also used as an indicator for assessing the infiltration of surface water into the aquifers.

2. Quantifying the rate of baseflow to streams: This is important in understanding the hydrogeological and biogeochemical processes, developing riverine ecosystem restoration strategies, formulating water budgets in a watershed and sustainable water resources management including proper allocation of water resources etc.

3. Hydrograph separation of the stream: This will elucidate streamflow hydrographs into various flow components generated from different hydrologic reservoirs. Improved water resource management necessitates a better understanding of runoff-generating processes as well as catchment functioning. It is imperative to understand the partitioning mechanisms of water components resulting in slow and fast pathways (baseflow and stormflow) and factors governing the partitioning for better anticipation of flood vulnerability in a basin as well as sustenance of streamflow supported by groundwater inflow in long periods of dry spells.

CONCLUSION

This novel methodology represents a transformative approach to understanding groundwater-surface water interactions, with far-reaching implications for water resource management in Ireland and beyond. While technical challenges—such hyporheic exchange complexity—require careful mitigation, the benefits are substantial. By generating high-resolution, spatially and temporally comprehensive, policy-relevant data, the project empowers decision-makers to safeguard groundwater-dependent ecosystems, optimize water allocation, and enhance climate resilience. The integration of radon-thoron tracing with geospatial tools and stakeholder collaboration has the opportunity to set a precedent for sustainable hydrological monitoring in an era of escalating climate uncertainty.

SUPLEMENTARY DATA

A comprehensive workflow has been produced for this project and is available in the following open-source link: 10.5281/zenodo.15088025

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EMERGING CONTAMINANTS: MICROPLASTICS, THE CURRENT STATE OF KNOWLEDGE

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ABSTRACT

Microplastics are small polymer particles, insoluble in water with a size range of 1-5000µm. They have become a serious environmental concern. These microplastics can originate from two primary sources: they can be intentionally manufactured (primary microplastics) for use in products like cosmetics and industrial applications, or they can result from the breakdown of larger plastic items (secondary microplastics) due to environmental factors such as sunlight, wind, and water action. Microplastics are ubiquitous, found in oceans, freshwater systems, soil, and even the air we breathe. They pose threats to ecosystems and wildlife, as aquatic organisms can easily ingest them, leading to potential bioaccumulation up the food chain. Moreover, microplastics can absorb and concentrate harmful chemicals from their surroundings, potentially transferring these toxins to living organisms. The widespread presence of microplastics in the environment has raised concerns about their impact on human health, as they have been detected in food, drinking water, and even human tissue. As a global issue, addressing the proliferation of microplastics requires concerted efforts in plastic waste management, product design, and consumer awareness to mitigate their environmental and health impacts.

Key words: *Microplastics, bioaccumulation, chemicals*

INTRODUCTION

Testing laboratories will require a concise analytical workflow to follow for extracting microplastics from soils and waters, this will typically involve several key steps. For soil samples, the process often begins with drying and sieving to remove larger particles. This is followed by dispersion of soil aggregates to release trapped microplastics. A crucial step is density separation, where the sample is mixed with a high-density solution (e.g., Zinc Bromide or Sodium Polytungstate) to separate microplastics from heavier soil particles. For both soil and water samples, organic matter removal is often necessary, using chemical digestion methods such as potassium hydroxide (KOH), hydrogen peroxide (H_2O_2) or enzymic treatments. These are preferred over acidic treatments, which can degrade certain plastic polymers. Filtration is then used to collect the microplastics, which can be further purified if needed. For water samples, large volume reduction through filtration or sieving is often the initial step. Throughout the process, measures must be taken to prevent sample contamination. Finally, the extracted microplastics are typically quantified and characterised using methods such as visual inspection, spectroscopic techniques (e.g., FTIR or Raman spectroscopy) and thermogravimetric techniques (e.g., Pyrolysis GC/MS). This workflow aims to isolate microplastics effectively while minimising their degradation or loss during the extraction process.

The state of international standards for the analysis of microplastics in soils and waters is still evolving, but significant progress has been made. In September 2023, the International Organisation for Standardisation (ISO) published ISO 24187, titled "Principles for the analysis of microplastics present in the environment." This standard is one of the first internationally recognised guidelines for microplastic testing and aims to advance harmonisation in this emerging field. Whilst BS EN ISO 24187:2023 outlined the general principles for the analysis of microplastics present in the environment, there is a requirement for more specific standardisation for each matrix type. BS ISO 5667-27:2025, titled "Water quality. Sampling. Guidance on sampling for microplastics in water" has been published March 2025. Further work through ISO 16094 is ongoing to produce standards for the analysis of microplastics in water by Vibrational spectroscopy methods (FTIR and Raman) and Thermo-analytical methods for waters (Pyrolysis GC/MS).

The U.S. Environmental Protection Agency (EPA) acknowledges the challenges in microplastics analysis and continues to prioritise developing methods for detecting and measuring microplastics in the environment. The EPA is focusing on establishing reliable and reproducible methods for sampling micro and nanoplastics, as well as using advanced analytical chemistry instruments to characterise and quantify total microplastics and different types of plastic polymers in water and sediment samples.

Regarding CEN (European Committee for Standardisation) standards, work through CEN TC/444/WG6 is ongoing and a formal standard for microplastics in solid matrices should soon be in official development.

Microplastic research is developing at an astronomical speed and we should all consider:

1. Ubiquitous presence: Microplastics have permeated virtually every ecosystem on Earth, from polar ice to deep oceans, and are found in soil, water, air. This widespread distribution means that exposure is nearly unavoidable for both wildlife and humans.

2. Environmental impact: Microplastics pose a threat to ecosystems and wildlife, particularly marine life. Animals can ingest these particles, leading to potential bioaccumulation up the food chain. The particles can also absorb and concentrate harmful chemicals, potentially transferring toxins to living organisms.

3. Human health concerns: While research is ongoing, microplastics have been detected in human blood, organs, and even the placenta. There are growing concerns about potential health risks, including increased risk of heart attacks, strokes, inflammation, and blood clotting. Some studies suggest links to cancer, immune system damage, reproductive problems, and developmental delays, although more research is needed to fully understand these impacts.

4. Increasing prevalence: It's estimated that 10 to 40 million metric tons of microplastics are released into the environment annually, with projections suggesting this could double by 2040. This escalating presence raises concerns about long-term environmental and health consequences.

5. Regulatory challenges: While some progress has been made in banning certain sources of microplastics (like microbeads in cosmetics), comprehensive regulations and standardised testing methods are still in development. This lack of uniformity makes it challenging to assess and address the full scope of the problem globally.

Given these concerns, continued research, policy development, and individual action are crucial to mitigate the potential long-term impacts of microplastics on environmental and human health.

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POSTERS

ESTIMATION OF NITRATE CONCENTRATION USING READILY AVAILABLE PHYSICOCHEMICAL PARAMETERS: A STRUCTURAL EQUATION MODEL

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POSTER ABSTRACT

Assessing regional-scale groundwater contamination is essential for managing water resources, ensuring clean water availability, and informing policy decisions. Challenges in groundwater contamination assessment include data availability and limited sample sizes. The physicochemical environment in groundwater is affected by external water and nitrogen input and its hydrogeological environment. Various indicators, including redox conditions, electrical conductivity (EC), pH, temperature, and nitrogen adsorption or release at the water-soil interface, play a crucial role in determining shallow groundwater quality. Additionally, redox reactions, ion exchange, and microbial activity regulate nitrogen concentrations in groundwater. These readily measurable indicators have demonstrated a strong correlation with nitrogen levels. However, due to the limited visibility and accessibility of groundwater, in-situ sampling for monitoring nitrogen across multiple shallow groundwater sites is both laborious and time-consuming. Moreover, automated online monitoring remains restricted by the high cost of equipment. Therefore, easily accessible parameters such as EC, dissolved oxygen (DO), oxidation-reduction potential (ORP), and pH are key indicators for predicting nitrogen concentrations and assessing groundwater contamination. This study employed a Structure Equation Modelling (SEM) technique to estimate the nitrate concentration from the measured physicochemical parameters (such as pH, temp, DO, ORP and EC). This study was conducted in the Bonet River catchment, which is comprised of Sligo and Leitrim counties. Water samples were collected from 32 randomly selected sites. Then, physicochemical parameters and NO_3 *concentrations were measured in the laboratory. Later, an SEM was fitted to estimate the direct and indirect relationships between the parameters and nitrate concentrations. Evaluating an SEM involves assessing the absolute fit indices and incremental fit indices. Absolute fit indices include chi-square test (*$p > 0.05$*), root mean square error of approximation (RMSEA < 0.08 (acceptable), < 0.05 (good)), and standardised root mean square residual (SRMR < 0.08 (acceptable)). Incremental fit indices include the comparative fit index and Tucker-Lewis Index (CFI/TLI > 0.90 (acceptable), and > 0.95 (good)). The presented SEM demonstrated a good fit for estimating nitrate concentrations (RMSEA: 0.044, SRMR: 0.061, CFI: 0.993, and TLI:0.978). The study also employed low-cost sensors to measure the parameters in real-time. Physicochemical data from these sensors were collected for six months, and nitrate concentrations were estimated using the SEM model. However, the number of observation sites was limited. Only four sensors were available to install. Future studies should concentrate on increasing the number of observations, either using low-cost sensors or manually collecting high temporal resolution data on physicochemical parameters to develop a better model and more accurate estimations of nitrate concentration.*

Keywords: *Structural Equation Model, Groundwater contamination, nitrate concentrations, low-cost sensor*

Estimation of nitrate concentration using readily available physicochemical parameters: a Structural Equation Model

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BACKGROUND

Nitrate (NO_3^-) pollution is a significant environmental and health concern; however, continuous monitoring is often hindered by the high costs and labor requirements associated with manual sampling and laboratory analysis. While direct nitrate sensors are expensive, low-cost sensors can reliably measure parameters such as temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), and oxidation-reduction potential (ORP). This study leverages Structural Equation Modeling (SEM) to estimate nitrate levels from these five parameters, enabling continuous and cost-effective nitrate monitoring using Low-Cost, real-time sensors.

AIM

To develop and deploy a Structural Equation Modeling (SEM) approach for the continuous estimation of nitrate (NO_3^-) concentrations in water using sensor-based measurements of temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), and oxidation-reduction potential (ORP).

RESEARCH QUESTION

Can an SEM-based model, developed using manually collected water quality data, reliably estimate nitrate concentrations from real-time sensor measurements of temperature, pH, EC, DO, and ORP in diverse field locations?

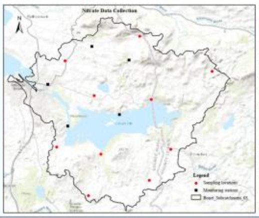
OBJECTIVES

1. To develop a Structural Equation Model (SEM) to estimate nitrate based on the five measured parameters.
2. To install water quality sensors at selected locations capable of continuously measuring temperature, pH, EC, DO, and ORP.
3. To integrate the developed SEM with real-time sensor data for the continuous estimation of nitrate levels in water.

MODELLING FRAMEWORK

WATER SAMPLING

STUDY AREA

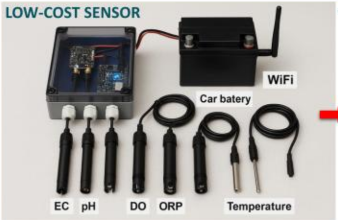


MEASURED PHYSICOCHEMICAL PARAMETERS

Manually collected samples

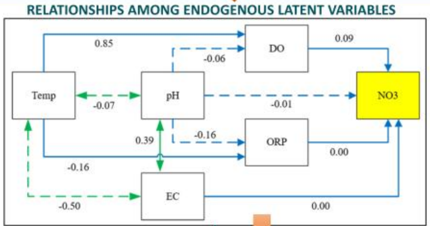
Site ID	NO_3N (mg/l)	Temp (°C)	pH	EC (uS/cm)	DO (mg/L)	ORP (mV)
Site 1	0.06	21.17	9.11	190.5	4.9	176.8
Site 2	0	21.17	7.17	158.13	4.51	203.9
Site 3	0.1	20.74	8.51	411.8	4.88	214.6
Site 4	0.3	21.32	4.9	118.5	5.85	269
Site 5	0.1	21.21	8.13	255.2	4.67	214.8
Site 6	0.13	21.14	8.86	356.2	5.14	215
Site 7	0.1	20.85	7.9	621.5	4.92	198.6
Site 8	0.18	20.96	8.65	597.1	4.56	166.9
Site 9	0.2	20.9	8.77	395.4	4.86	203.9
Site 10	0.08	20.91	8.76	329.7	5.02	180.7

LOW-COST SENSOR



Station ID	Measured NO_3N (mg/l)	Temp (°C)	pH	EC (uS/cm)	DO (mg/L)	ORP (mV)
Station 1	0.17	17.93	9.15	432.75	3.50	280.57
Station 2	0.14	20.31	8.89	335.23	5.77	385.89
Station 3	0.18	18.00	7.34	238.31	3.16	183.57
Station 4	0.23	17.52	7.83	233.43	2.60	259.55
Station 5	0.24	20.17	8.33	367.00	8.11	129.06

RELATIONSHIPS AMONG ENDOGENOUS LATENT VARIABLES

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Comparative Fit Index (CFI):                     0.993
Tucker-Lewis Index (TLI):                        0.978
Root Mean Square Error of Approximation (RMSEA): 0.044
Standardized Root Mean Square Residual (SRMR):   0.061
```

Common Model Fit Standards in SEM

Fit Index	Excellent Fit ✅	Acceptable Fit ⚠️	Poor Fit ❌
CFI	≥ 0.95	0.90 – 0.94	< 0.90
TLI	≥ 0.95	0.90 – 0.94	< 0.90
RMSEA	≤ 0.05	0.06 – 0.08	> 0.08
SRMR	≤ 0.08	—	> 0.08

HIGHLIGHTS

- ✅ Developed an **SEM model** to estimate nitrate from five common water quality parameters.
- 💧 Manual field sampling was used to build and validate the model.
- 📈 Parameters used: **Temperature, pH, EC, DO, ORP**.
- Enables **continuous nitrate estimation** using low-cost water quality sensors.
- **Cost-effective alternative** to expensive direct nitrate sensors.
- 🌏 Scalable solution for **real-time water monitoring** in remote or resource-limited areas.
- 🔄 Bridges the gap between **lab-based data** and **field-deployable monitoring**.

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Ollscoil Teicneolaíochta an Atlantaigh

Atlantic Technological University

CONNACHT-ULSTER ALLIANCE

MINKE

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Arghadyuti Banerjee

Leo Creedon

Noelle Jones

Salem Gharbia

GROUNDWATER FORECASTING AND CLIMATE CHANGE IMPACTS PROJECT

Joan Campanyà[1], Philip Schuler[2], Henning Moe[1], Monika Kabza[1], Sonja Masterson[3], David Tynan[1], Jon Hunt[1], Meabh Banrion[1], Babhinn Anders[1], Colin Fitzgerald[1], Ted McCormack[4], Owen Naughton[5], Barry Coonan[6]

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POSTER ABSTRACT

Observations and climate change projections for Ireland indicate an increase in the frequency and magnitude of extreme meteorological events, including droughts and flooding.

In response to the challenges arising from climate change, the Department of the Environment, Climate and Communications is funding the 4-year (2023-2027) 'Groundwater Forecasting and Climate Change Impacts project', led by the Geological Survey Ireland. The Groundwater Forecasting and Climate Change Impacts project assesses the impacts of meteorology and climate change on groundwater and characterises where groundwater resources are most resilient or susceptible to significant changes from climate change.

The main objectives of the project are to:

1. *Maintain and expand the climate change related groundwater level monitoring network, focussing on recording droughts and floods.*
2. *Develop a data management system for integrating datasets and products from the project.*
3. *Examine the hydrogeological aspects of vulnerability or resilience of Irish groundwater systems to climate change impacts.*
4. *Develop methods and tools for modelling groundwater levels in Ireland at a national scale.*
5. *Deliver systems, tools, methods and workflows for groundwater level forecasting and the assessment of climate change impacts.*
6. *Upgrade and execute satellite-based mapping and monitoring tools for groundwater flood mapping previously developed by GSI.*

This poster provides an update on the status of the project and presents the key deliverables.

An Roinn Comhshaoil,
Aeráide agus Cumarsáide
Department of the Environment,
Climate and Communications

Groundwater Forecasting and Climate Change Impacts

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Joan Campanyà, Henning Moe, Monika Kabza, David Tynan, Jon Hunt, Meabh Banrion, Babhinn Anders, Colin Fitzgerald (*MKO*), Philip Schuler (*CDM Smith*),
Ted McCormack (*Geological Survey Ireland*), Sonja Masterson (*AquaStrata*), Owen Naughton (*Department of Built Environment, South East Technological University*), Barry Coonan (*Met Éireann*)

Observations and climate change projections for Ireland indicate an increase in the frequency and magnitude of extreme hydroclimatic events, including droughts and flooding. In response to the challenges arising from climate change, the Department of the Environment, Climate and Communications is funding the 4-year (2023-2027) 'Groundwater Forecasting and Climate Change Impacts project'. Led by Geological Survey Ireland the project, through a series of work packages, assesses the impacts of meteorology and climate change on groundwater and characterises where groundwater resources are most resilient or susceptible to significant changes from climate change.

Main Work Packages

Groundwater Monitoring

Objective:

To maintain and expand the climate change-related groundwater level monitoring network, focussing on recording droughts and floods.

Completed to date:

- Completed 5 monitoring rounds across 25 turloughs and 55 boreholes.
- Installed 16 of 38 planned boreholes.

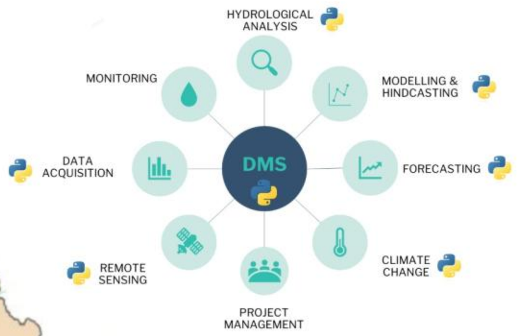
Data Acquisition and Management System

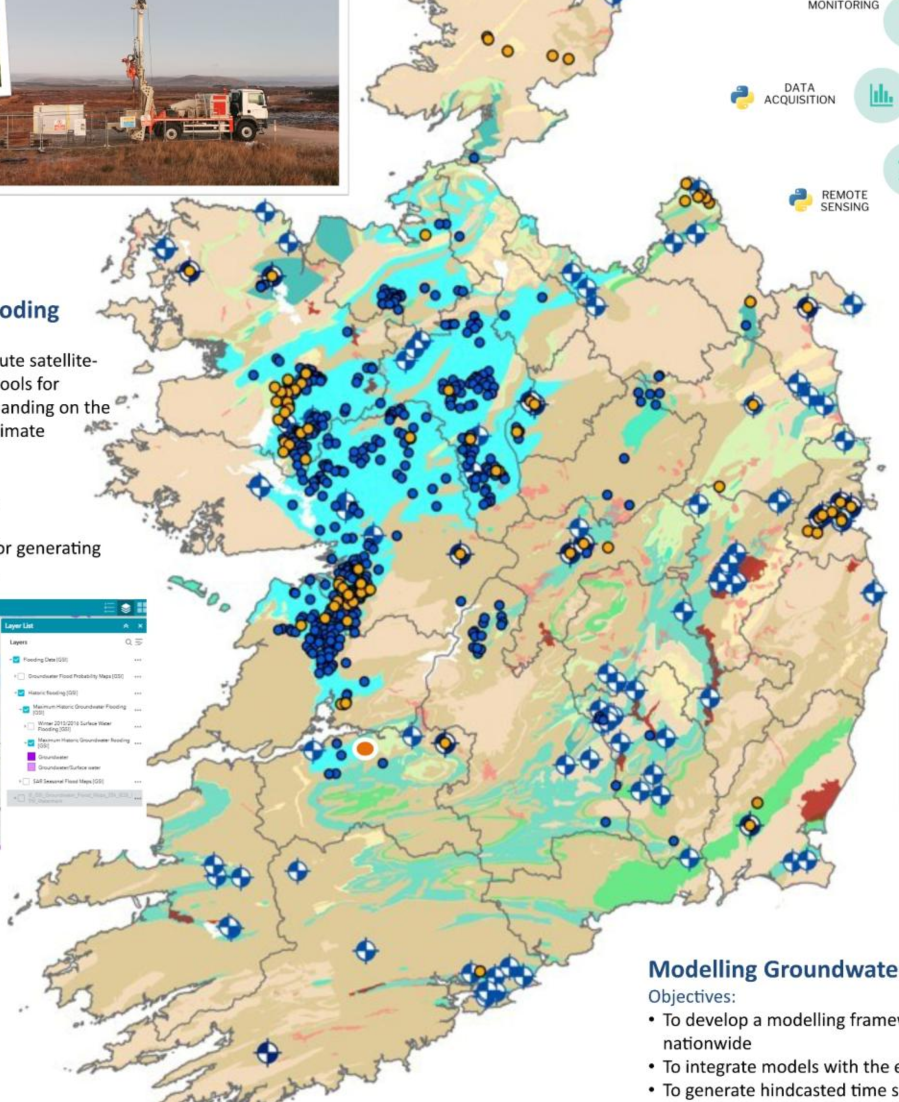
Objective:

To develop a data management system for integrating datasets and products from the project.

Completed to date:

- The system is implemented and updated as required.





Remote Sensing and Flooding

Objective:

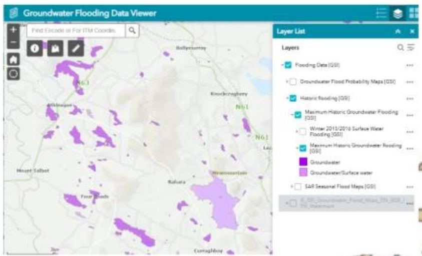
To upgrade, implement and execute satellite-based mapping and monitoring tools for groundwater flood mapping, expanding on the GWFlood (2016-2019) and GWClimate (2020-2022) GSI projects.

Completed to date:

- Workflows for flood mapping

Working on:

- Implementing the workflow for generating satellite derived hydrographs.



Hydrogeological Analysis

Objectives:

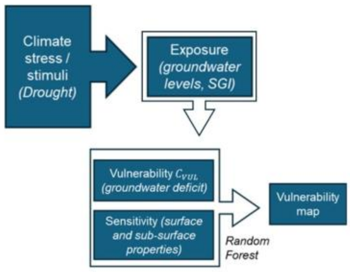
- To examine the hydrogeological aspects of vulnerability and resilience of Irish groundwater systems to climate change.
- To develop a trial groundwater flood susceptibility map to identify at-risk areas.

Completed to date:

- Draft of the trial groundwater flood susceptibility map.

Working on:

- Assessing the vulnerability and resilience of Irish groundwater systems to climate change impacts.



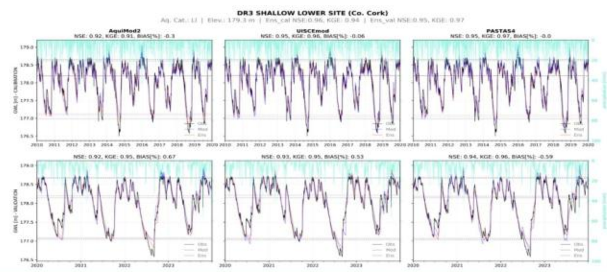
Modelling Groundwater Levels

Objectives:

- To develop a modelling framework for groundwater levels nationwide
- To integrate models with the existing data management system.
- To generate hindcasted time series for historical analysis.
- To fill data gaps in historical groundwater datasets.

Completed to date:

- Work package close to completion.



Forecasting and Climate Change

Objective:

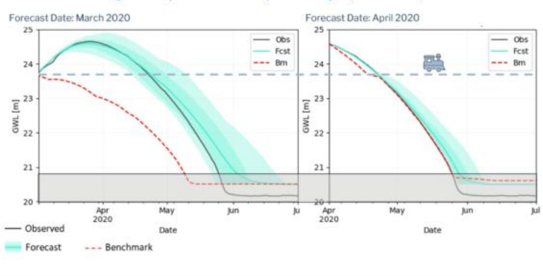
- To develop forecasting tools for groundwater levels in Ireland
- To evaluate the effects of climate change on future groundwater levels across Ireland.

Completed to date:

- Prototype of the forecast system.

Working on:

- Finalising forecast system for groundwater levels.



MKO
CDM Smith
MET éireann The Irish Meteorological Service
SETU
AquaStrata

IN-SITU MEASUREMENT OF TRACER TRANSPORT RATES IN PEAT USING POINT DILUTION TESTING AND TIME DOMAIN ELECTRICAL RESISTIVITY TOMOGRAPHY

Raymond Flynn[1], Vicky Preece[1], Shane Donohue[2] and Jonathan Chambers[3]

1. School of the Natural and Built Environment, Queen's University Belfast
2. School of Civil Engineering, University College Dublin
3. British Geological Survey

POSTER ABSTRACT

Despite underlying over one fifth of Ireland, how groundwater flows through Irish peats remains poorly defined. Nonetheless this information proves necessary for assessing the wider impacts of upland developments in areas covered by blanket bog, including, inter alia, wind power facilities and associated access routes. However, high levels of heterogeneity, coupled with elevated sensitivity to changes in pore water pressure, exhibited by peats during conventional permeability testing, make characterisation of groundwater flow rates challenging.

Single well (point) dilution tracer testing provides a means of estimating the magnitude of groundwater velocity by monitoring changes in tracer concentration over time. Combining this information with hydraulic gradient data has potential for determination of hydraulic conductivity, without the need to impose changes in head. Although installation of piezometers to measure the magnitude of gradients can prove easier and less expensive in peats than in other media, determination of the direction of groundwater flow remains complex in heterogeneous media.

Geophysical methods provide a non-invasive means for subsurface characterisation, which may be employed with artificial tracer testing to characterise hydrogeological processes. For Irish blanket bogs, the introduction of elevated conductivity tracer into bog groundwater, which typically has low specific electrical conductance, displays significant potential to allow quantification of flow and mass transport.

The Geological Survey of Ireland-funded Peatland Hydrogeological Assessment for Slope Stability Evaluation (PHASSE) short research project aims to test this concept. Preliminary application at the Garron Blanket Bog Hydrological Research Catchment, Co. Antrim employed point dilution tests and the British Geological Survey PRIME system to track groundwater flow in shallow (<1m deep) peat. Multiple level monitoring of point dilution test results in 50mm diameter tracer injection well suggested high levels of hydraulic conductivity anisotropy with depth, with the uppermost 20cm proving significantly more permeable than peat at 80cm below ground surface. These findings suggesting groundwater flows preferentially in the shallower (less decomposed) deposit. This is corroborated by ERT monitoring, which detected the migration of a thin plume of higher conductivity water 1m down gradient, less than one day following injection. Findings highlight the value of characterising geological conditions to better understand subsurface flow and transport. Further work to be undertaken in PHASSE will focus on assessing the precision of this method, and the potential of the tracers employed to affect geotechnical properties / interact with the peat.

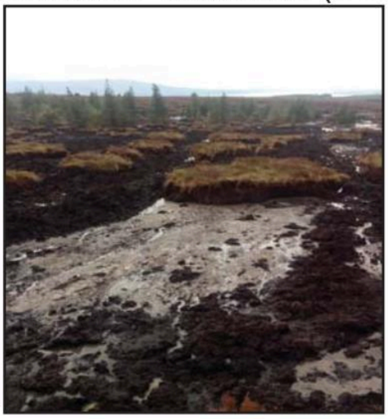
Key words: *Peat, Blanket Bog, Groundwater Flow, Tracer Test*

In-Situ Measurement of Tracer Transport in Peat Using Point Dilution Testing and Time Domain Electrical Resisitivity Tomography

Raymond Flynn (QUB), Vicky Preece (QUB), Shane Donohue (UCD) & Jonathan Chambers (BGS)

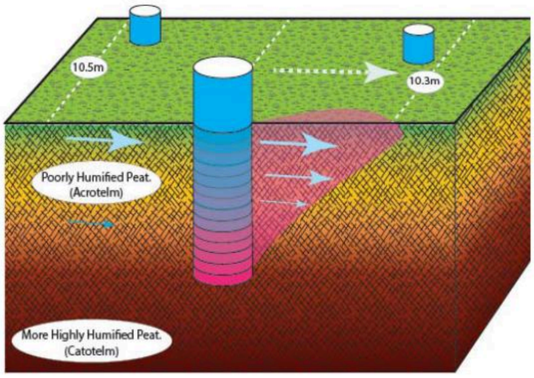
Blanket Bogs and Groundwater

On-shore wind energy forms a significant and growing element of Ireland's electricty generation capacity. Most large generation facilities occur in upland areas, typically in settings containing extensive blanket peat. Recent catastrophic peat slope failures across Ireland have highlighted the need for an improved understanding of how groundwater flows through bogs. The Geological Survey of Ireland-sponsored Peatland Hydrogeological Assessment for Slope Stability Evaluation (PHASSE) program applies tracer testing and geophysical methods to investgiate this issue.



Right: Blanket bog slope failure, Co. Leitrim. More knowlegdge of how changes in groundwater flow affect slope stablity is needed to reduce the risk of similar occurences.

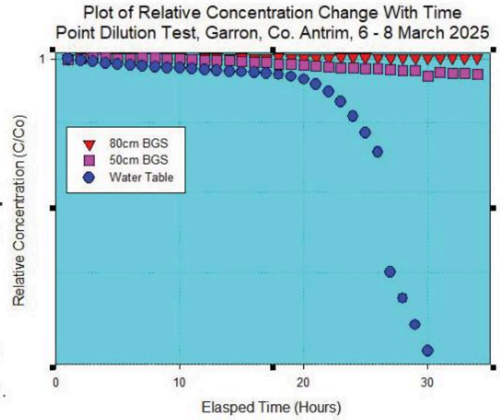
Point Dilution Testing



Aim: To measure flow rates by

- o Injection of salt tracer into well.
- o Monitoring upper 1m from water table to well screen base to assess vertical heterogeneity in K.
- o Quicker declines in conc. reflect higher groundwater flow rates.

Right: Tracer test results indicate a large decline in flow with depth.

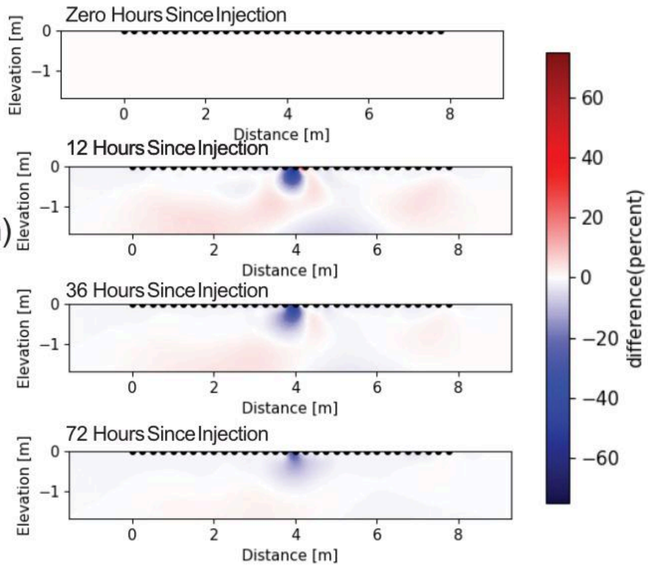


Geophysical Testing - Background

Aim: To non-invasively monitor how tracer moves in 3D, relying on

- o a contrast in low conductivity (<150uS/cm) bog groundwater and tracer solution (Co:40,000uS/cm), monitored using time domain ERT under passive hydraulic gradients.

- o Initial tests monitored at 1m down gradient from injection point with BGS PRIME system (left).



Right: Results of tracer test at Garron, using PRIME data, show rapid breakthrough in uppermost layer of low humification peat.

Prelimiary Findings

Initial PHASSE point tracer test / PRIME measurements show that groundwater can travel quickly through Irish blanket peat. Injection well tracer concentration monitoring revealed flow to occur predominantly in the upper least decomposed layers of peat. This is proved consistent with the results of ERT monitoring, reflecting the capacity of this approach to provide an improved understanding of peatland hydrogeology and a potential means to better define hydrogeological processes responsible for peat slope failure.

British Geological Survey — Geological Survey Suirbhéireacht Gheolaíochta Ireland | Éireann — University College Dublin

THE IDENTIFICATION AND DELINEATION OF CANDIDATE TURLOUGHS WITH VERY SMALL PLAN AREAS FROM HIGH RESOLUTION REMOTE SENSING DATA

Chan-Kinsella, A.[1], Tedd, K.[1], Meehan, R.[2], Von Beaumont, R.[3], Duncan, N.[3], McCormack, T.[1] Corresponding Author Email Address: annamei.chan-kinsella@decc.gov.ie

[1]Geological Survey Ireland, [2]Talamhireland, [3]TOBIN

POSTER ABSTRACT

The GWFlood Project was initiated in 2016 following the floods of winter 2015/2016, to address the gaps in karst groundwater flooding data available across Ireland, and to further understand groundwater flooding. Karst feature mapping conducted in the field at field scale as part of Geological Survey Ireland's GW3D project during Summer 2024 identified a number of potential turloughs of small plan area which had not yet been recorded.

This project investigated the best methodology to map these features remotely. High resolution Sentinel-2 imagery, and Vivid Standard remotely sensed data were both used, as well as local groundwater level data, and further field mapping in the Winter season to verify and better characterise the features. The features were then manually digitised from the remotely sensed data.

The inclusion of these smaller features, not previously recognised from previous mapping, is significant at local scale, and provides improved information for Planning decision makers, ecologists, engineers, farmers, and local heritage groups. Further future work will investigate the potential to automate this methodology using high-resolution LIDAR data.

Key words: *Karst, flood, turlough*

The Identification and Delineation of Candidate Turloughs with Very Small Plan Areas from High Resolution Remote Sensing Data

An Roinn Comhshaoil, Aeráide agus Cumarsáide
Department of the Environment, Climate and Communications

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

TOBIN

AnnaMei Chan-Kinsella[1], Katie Tedd[1], Robbie Meehan[2], Rebecca Von Beaumont[3], Natalie Duncan[3], Ted McCormack[1]

[1]Geological Survey Ireland, [2]Talamhireland, [3]Tobin Consulting Engineers

Introduction

The GWFlood project was a 3-year programme initiated in 2016 by Geological Survey Ireland following the floods of winter 2015-2016, to address the gaps in karst groundwater flooding data available across Ireland and to further understand groundwater flooding, with a particular focus on turloughs.

Karst feature mapping in the field, as part of Geological Survey Ireland's GW3D project during Summer 2024, identified 13 potential turloughs of small plan area. Of which 2 had previously been mapped, and of which 11 had not yet been recorded.

This project investigated the best methodology to map these features remotely, exploring previous methods used by Campanya & McCormack for the GWFlood project, which utilised synthetic aperture radar (SAR) from the Sentinel-1 mission to delineate the maximum flood extent of the features, cross-referenced with topographic data to calculate the elevation of the feature.

This method was tested on these features, but it was found that the features were not large enough to be successfully detected and defined. So, in the case of these features, another method had to be employed.

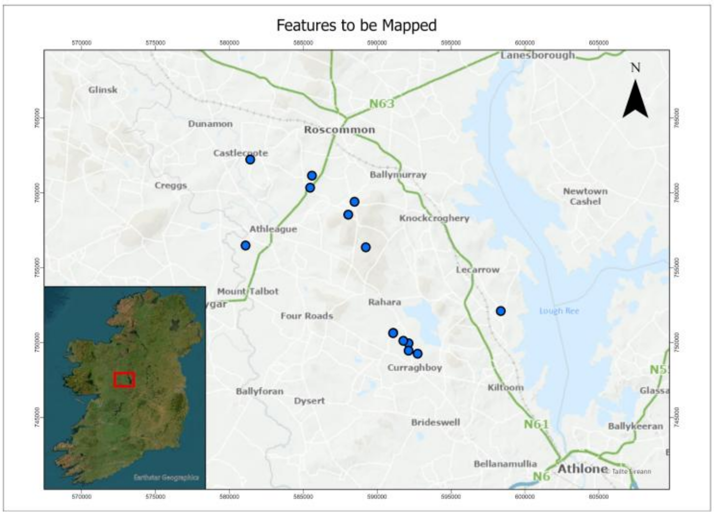


Image 1: Map of features to be mapped in Roscommon area based on Summer 2024 fieldwork

Methodology

- In order to choose an appropriate timeframe for the desk-based analysis, using rainfall data and groundwater level data, the "wet" years were identified
- An image search was conducted focusing on the "wet" years, using Sentinel-2 L2A imagery from EU Copernicus
- A criteria of "flood" duration, and repeat events, was used to determine the potential of the feature being a turlough
- The features were digitised in ArcGIS Pro, using Sentinel-2 Normalised Difference Water Index (NDWI) and True Colour imagery. The extent of the feature was determined based on the visible water extent in the imagery
- The resolution of the Sentinel-2 imagery was too coarse to accurately digitise a number of the features due to their small scale. The features are still identifiable from the Sentinel-2 true colour images, although unclearly. The features were verified, and digitised using the Digital Globe imagery. The use of LIDAR may be a suitable solution for work of this scale

Outcomes

- The maximum area extent of 10 features were manually digitised
  - Evidence from field mapping suggests that 3 are likely to be surface water features
  - 1 feature of original 13 did not meet flood duration criteria
  - 2 of 13 features are included in previous GWFlood mapping
- Extent of the remaining 7 features, and the 3 surface water features will be verified with field checks in the 2025 Spring

Image 2: Sentinel-2 L2A NDWI, 17 December 2019, EU Copernicus

Image 3: Mapped feature, based on NDWI 17 December 2019

Image 4: Field image, 13 December 2024, Robbie Meehan

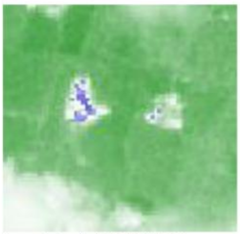


Image 5: Sentinel-2 L2A NDWI, 21 November 2020, EU Copernicus

Image 6: Mapped feature, based on NDWI 21 November 2020

Image 7: Field image, 13 December 2024, Robbie Meehan

A selection of mapped features:

Image 8: Mapped feature, based on Sentinel-2 True Colour 19 January 2020

Image 9: Mapped feature, based on Digital Globe 14 April 2020

Image 10: Mapped feature, based on True Colour 01 March 2020

Image 11: Mapped feature, based on NDWI 05 January 2021

Image 12: Mapped feature, based on True Colour 29 January 2025

Conclusions & Future Work

The methods used in this project are suitable for mapping smaller groundwater flooding features. The scale of these features are often too small for DTM verification, and in this case the resolution of Sentinel-2 imagery. As such the features had to be manually mapped, however where available, it could be possible to use LIDAR.

The inclusion of these smaller features, not previously recognised from previous mapping, is significant at local scale, and provides improved information for planning decision makers, ecologists, engineers, farmers, and local heritage groups.

Future work for this project will involve field checking of features, continued work in other areas of interest, and an investigation into the viability of an automated process using LIDAR.

Acknowledgements: Special thanks to all that have been involved in the field mapping for this project Charlotte Bennet, Corine Oggel, Darren Clarke, Joe Greene, Karina O'Donnell, Rhianna McDonnell, Tristan Martin, Philip Bourke, Thomas Leavy, Emer Delargey, Abigail O'Brien

References: Campanya, J., McCormack, T., Doherty, D., Schuler, P., Kabza, M., Mullarkey, E., & Naughton, O. (2020). REMOTE SENSING FOR GROUNDWATER FLOOD MAPPING, MONITORING, AND SHORT- AND LONG-TERM FORECASTING. Irish National Hydrology Conference 2020.

Author Contact: *annamei.chank@gmail.com*

GSI DATA, PRODUCTS AND MODELS FOR GROUNDWATER AND GEOTECHNICAL PURPOSES

Sophie O'Connor, Beatriz Mozo Lopez
Geological Survey Ireland

POSTER ABSTRACT

Over many years, Geological Survey Ireland has developed several services in different formats to help pull together information about the subsurface, to present it in an organised manner and to portray it in three dimensions. Underpinned by the organisation's commitment to open data and re-use of public sector information, these services are:

- *National Geotechnical Borehole Database (NGBD)*
- *Geotechnical Viewer*
- *Geotechnical products for download*
- *3D models and model viewer*
- *Peat mapping, related databases, projects, publications, and funded research*

The next step is to survey our stakeholders for future outputs. Please share your insights at the QR code on the poster.

Extended Abstract

Assembled over several decades, the National Geotechnical Borehole Database (NGBD) has expanded with the submission of ground investigations that have been carried out ahead of development projects by the private and public sectors. It acts as a secure, national repository and is a valuable resource for:

- *planning and optimising future ground investigations;*
- *understanding the subsurface and geoscience linkages;*
- *for helping construct 2D and 3D models.*

For ease of access, data and reports from the NGBD are published on the Geotechnical Viewer, freely available to all. The online Geotechnical Viewer displays several thousand georeferenced ground investigations. Recent developments utilising the NGBD include new nationwide geotechnical datasets which include particle size analysis, plasticity and in-situ permeability test results.

With time and technical and software advances, Geological Survey Ireland has produced 3D geological models using the NGDB and other GSI datasets. Our 3D models can assist with:

- *Resource (water and geothermal) mapping;*
- *Understanding and characterising urban geology, with potential relevance for basement impact assessment, Sustainable Drainage Systems (SuDS), flooding and, subsurface management;*
- *Optimising geotechnical investigation, design and construction;*
- *De-risking human activities from impact of our subsurface environment;*
- *Investigating impact of human activities on environment around and beneath us, e.g., dewatering;*
- *and informing policy, planning, protective and climate adaptation measures.*

3D geological models allow everyone to visualise the subsurface and can be used to communicate the geoscience behind projects, thereby making defensible decisions visible. The 3D models are easily accessible on GSI's 3D model viewer with Interactive and Augmented Reality functionality. To tailor outputs to stakeholder needs, attendees are invited to fill in the survey within the QR code.

GSI data*, products and models for groundwater and geotechnical purposes

An Roinn Comhshaoil, Aeráide agus Cumarsáide
Department of the Environment, Climate and Communications

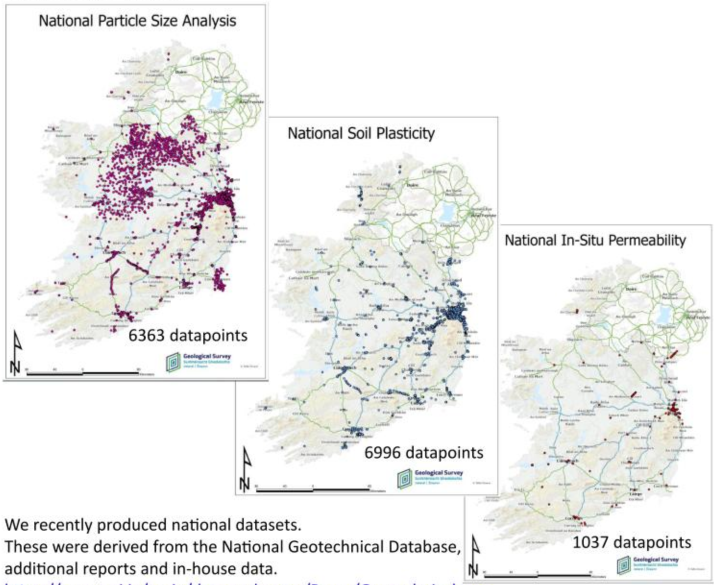
Beatriz Mozo Lopez, Sophie O'Connor

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

*Quaternary, geotechnical and geohazards data

National Geotechnical Borehole Database (NGBD) & geotechnical viewer

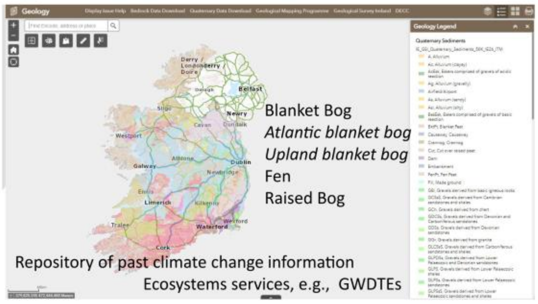
The national geotechnical database comprises digital and hard copy records of thousands of ground investigations. Many are downloadable directly from the geotechnical viewer. If you require a report not yet scanned, please contact geologicalmappinginfo@decc.gov.ie with the 'REPORTID' number.



We recently produced national datasets.
These were derived from the National Geotechnical Database, additional reports and in-house data.
https://www.gsi.ie/en-ie/data-and-maps/Pages/Geotechnical.aspx

Peat

~20% of the area of Ireland is mapped as peatlands
(Source: GSI Quaternary Sediments map).



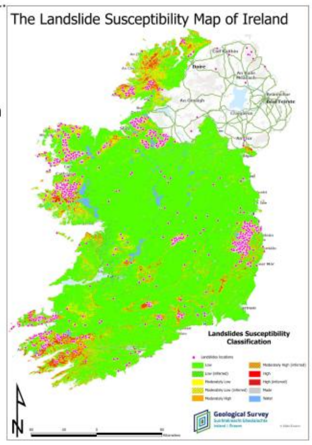
Peat poses challenges for infrastructure and development. Climate change will likely lead to more intense rainfall events - a known trigger for slope failure on peatlands.

Peat landslides can result in ecological losses, disruption to water supplies and infrastructure, and even fatalities in the past.

Land use changes (e.g., renewables, rewetting, coastal inundation) warrant further understanding of peat. GSI/NPWS joint project commissioned to assess role of land use change in altering peatland properties; findings were recently published.

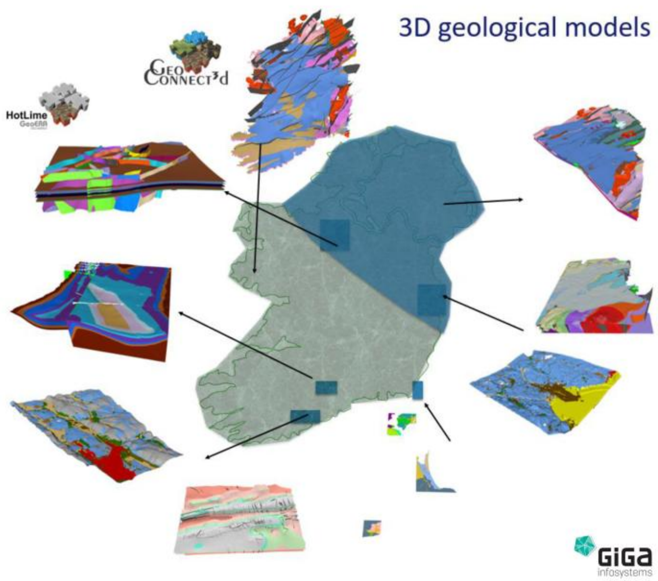
GSI fund and support peat research including short calls.

The internal Peat Group acts as a central hub to address varied peat issues and stakeholder queries.



3D geological models

There are now eleven 3D geological models on GSI's model viewer https://geo3d.gsi.ie
No specialist software needed.
Interactive – users can produce and save virtual borehole logs & cross-sections.
AR functionality on your mobile phone.



Outreach, collaboration, best practice


sustainability
MDPI
Article
Geoscience for Cities: Delivering Europe's Sustainable Urban Future

Sustainability **2024**, 16, 2559. https://doi.org/10.3390/su16062559
https://www.mdpi.com/2071-1050/16/6/2559 Open access

Did you know…
we engage with other European geological survey organisations (GSOs) to maintain best practice for our data, outputs and service. We contribute to factsheets, documentaries, peer-reviewed journals, documentaries, working groups and research proposals.

8.WPGI 2024

What next?

Have your say and take the GSI Stakeholder survey on geotechnical data by scanning the QR code

GSI stakeholder survey on geotechnical data

In addition to the geotechnical viewer and products, GSI also provide the Verified Boreholes with Logs https://www.gsi.ie/en-ie/data-and-maps/Pages/Bedrock.aspx#verified in download and viewer formats. Additional maps and reports are searchable on our Goldmine archive resource https://secure.decc.gov.ie/goldmine/index.html and also our data for planning pages.

In conjunction with: Charise McKeon, Michael Sheehy, Jim Hodgson, Thomas Leavy (Peat Group); NPWS, Fehily Timoney (Peat failures); Ted McCormack (North Cork 3D model), GiGa InfoSystems, iCRAG, (3D models & model viewer).

EARLY WARNING GROUNDWATER DROUGHT SYSTEM: UNDERSTANDING AQUIFER RESPONSES TO CLIMATE EXTREMES ACROSS IRISH CATCHMENTS

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[a] *School of Transport and Civil Engineering, Technological University Dublin*
[b] *Spatio-Temporal Environmental Epidemiology Research (STEER) Group, Technological University Dublin*

POSTER ABSTRACT

Predicting groundwater drought is challenging, particularly in Ireland's temperate climate and complex (hydro)geology. Groundwater catchments are unique in terms of their recharge mechanism(s), influenced by diverse geology, soil profiles, and surface water-groundwater interactions. Accordingly, "surface to aquifer" ensemble-based modelling likely represents the best approach for groundwater drought across Irish hydrogeology.

The current study aims to characterise and subsequently predict groundwater behaviour under climate extremes (droughts) by integrating drought indicators with antecedent climate and local hydrogeological setting using machine learning (ML) approaches. Groundwater level (GWL) time series from 100 stations covering the period 2010 to 2023 were used for drought investigation using the Standardised Groundwater Index (SGI). The indicator was validated using the 1-in-100-year 2018 drought event, identifying SGI < -1.5 as a suitable drought threshold.

Groundwater droughts were identified using eXtreme Gradient Boosting (XGB) algorithms trained on meteorological factors. Model performance varied considerably; therefore, top-performing models with an area under the receiver operating characteristic (ROC) curve (AUC) greater than 0.8 were selected and hydrologically profiled to assess the influence of catchment parameters on drought occurrence. These high-performing models were then integrated into an ensemble framework to improve prediction accuracy by incorporating local hydrogeological features.

Results indicate that the first ensemble learner effectively predicts drought in areas with short groundwater memory (71 days) and low elevation. Non-parametric bivariate tests confirmed significant associations this learner profile for groundwater memory (p=0.005), soil drainage (p=0.008), subsoil type, (p=0.03) and bedrock type (p=0.03). Further model training revealed that topographical (i.e., elevation) significantly enhanced predictive performance.

Key words: *Drought, aquifer, prediction, climate extremes*

DEEP GEOTHERMAL RESEARCH IN TULLAMORE, CO. OFFALY

Tristan Martin, Philip Bourke, Thomas Leavy, Emer Delargey, AnnaMei Chan-Kinsella, Abigail O'Brien, Markus Pracht, Russell Rogers, Taly Hunter Williams, Rory Dunphy, Sarah Blake

GEOLOGICAL SURVEY IRELAND

POSTER ABSTRACT

This poster presents a preliminary report on the research Geological Survey Ireland has carried out on the Clonminch borehole in Tullamore, Co. Offaly with a view to advancing our knowledge of deep geothermal resources in the area.

This report presents the methods of data acquisition, the initial results and some preliminary interpretations of these results.

The main outputs for this project included: 1) downhole geophysics, 2) Distributed Temperature Sensing (DTS) analysis, 3) a lithological log, 4) X-ray fluorescence (XRF) analysis, and 5) a fracture log.

Downhole geophysical logging was carried out on the Clonminch borehole by Robertson Geo, including: a composite log, a fluid log, a triple sonic log and a televiewer log. DTS logging of the borehole has been carried out by Geological Survey Ireland graduate geologists at regular time intervals since the borehole was completed. A core log was completed by Markus Pracht, which includes a lithological description of the core and a stratigraphic interpretation of the rock units. XRF analysis was completed by Geological Survey Ireland graduate geologists on the core using 2 handheld S1 Titan Bruker XRF units. A fracture log of the core was also carried out by Geological Survey Ireland graduate geologists. A total of 7006 fractures were logged and classified.

The combination of these outputs serves to characterise the Clonminch borehole in great detail and thus provide information on the deep geothermal potential of the area.

HYDRO-GEOTECHNICAL PROPERTIES OF PEAT BUNDS USED IN THE RESTORATION OF RAISED BOGS

Sajjad Ahmad[1]*, Laurence William Gill[1], David Igoe[1], Shane Regan[2]
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[2] National Parks and Wildlife Service

POSTER ABSTRACT

Peatlands provide ecosystem services by regulating hydrology and serving as significant carbon sinks. Degradation due to artificial drainage and peat cutting has changed their natural hydrological functions, transforming peats into net carbon sources and biodiversity lacunae. However, in recent years there has been action to reverse this damage using different strategies to restore healthy wetland ecosystems. One widely used restoration technique involves the construction of peat bunds or berms to regulate water flow and facilitate rewetting of cut-away bogs. However, the effectiveness of these bunds depends on the hydro-geotechnical properties of peat, which have received few studies to date, highlighting the need for further investigation to optimize their design and long-term performance.

Here we show the hydro-geotechnical properties of peat bunds through a combination of laboratory and field testing. Falling head permeability tests and in situ slug tests were conducted to determine the saturated hydraulic conductivity. Other analysis included specific yield capacity, volumetric water content, and organic content which are critical parameters to calculate peat water retention capacity. Seepage through the bunds has been simulated using HYDRUS-2D software, whilst Plaxis-2D modelling has been used to examine consolidation through oedometer tests using a ShearScan Pro motorized system to better understand the compressibility of peat material.

Preliminary results demonstrate that peat bunds show variable hydraulic conductivity, likely due to peat heterogeneity caused by the JCB bucket compression during bund construction. This variability effects the net seepage rate through the bunds which is being included in hydraulic / hydrological models of the overall linked bund systems in order to understand the dynamics of the restoration techniques and resultant water levels in more detail. Overall, peat properties and numerical models for seepage and consolidations offers valuable insights into the hydrological performance of peat bunds in restoration projects.

Hydro-geotechnical properties of peat bunds used in the restoration of raised bogs

Sajjad Ahmad[1*], Laurence William Gill[1], David Igoe[1], Shane Regan[2]

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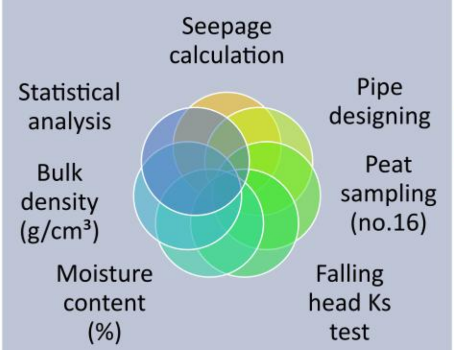
[2] National Parks and Wildlife Service

Problem

1. Degradation due to artificial drainage and peat cutting.
2. Lacking understanding of hydro-geotechnical properties of peat bund effectiveness
3. Optimizing hydrological modelling.

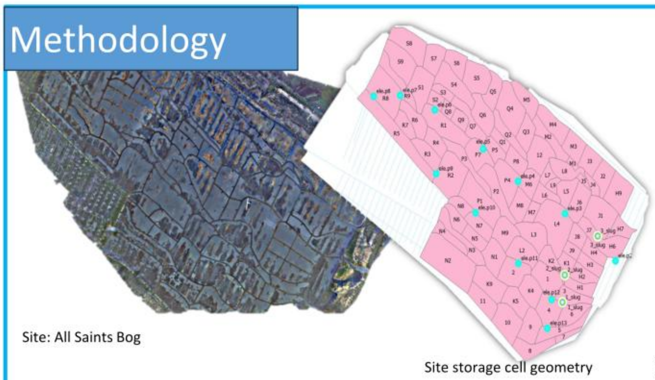
Analysis



Goal

To characterise the hydro-geotechnical properties of peat used in bund construction, with the aim of optimising design parameters and improving the hydraulic performance of restoration features in degraded raised bogs.

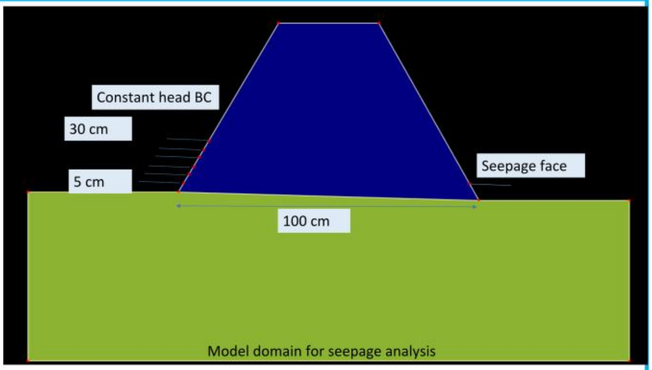
Methodology



Site: All Saints Bog

Site storage cell geometry

Permeameter tube (falling head test)



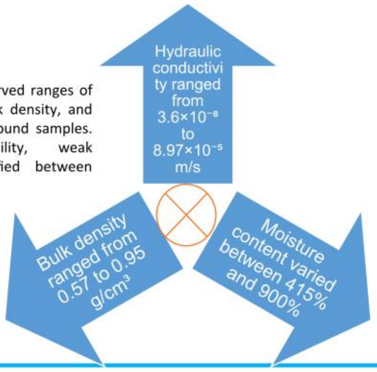
Model domain for seepage analysis

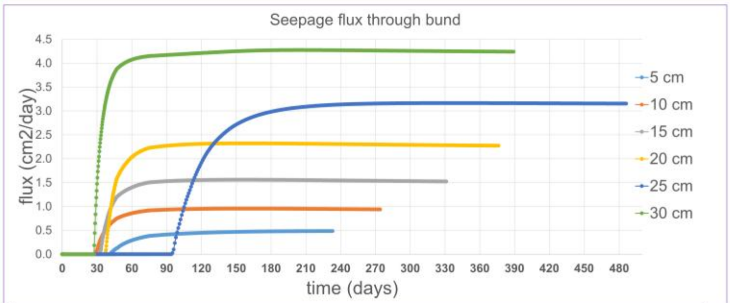
Data analysis

Statistical analyses were conducted to characterise the physical properties of peat. Moisture content and bulk density exhibited a moderate positive association, whereas hydraulic conductivity was highly variable and showed weak correlations with the measured parameters. A scatterplot and multiple linear regression model accounted for 44% of the variability in hydraulic conductivity; however, none of the predictors were statistically significant. These results indicate that hydraulic conductivity is more strongly governed by bund compaction and construction-related heterogeneity than by bulk geotechnical properties, with direct implications for seepage performance.

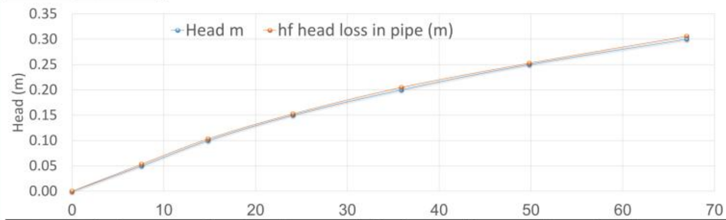
Results

Diagram showing the observed ranges of hydraulic conductivity, bulk density, and moisture content in peat bund samples. Despite wide variability, weak correlations were identified between these parameters.





Simulated seepage flux through the peat bund under six constant head levels (5–30 cm).



A pipe with diameter of 1.1 mm was modelled using the Darcy–Weisbach equation to handle equivalent discharge. $h_f = f\left(\frac{L}{D}\right)\left(\frac{v^2}{2g}\right)$

Conclusion

Peat bund performance is highly influenced by construction-induced heterogeneity, with hydraulic conductivity showing significant variability. A multiscale data would be required for hydrological modelling of these sites.

RESEARCH IRELAND CENTRE FOR APPLIED GEOSCIENCES

DESIGN OPTIMIZATION OF LARGE-SCALE SHALLOW GEOTHERMAL SYSTEMS FOR DISTRICT HEATING AT UCD

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[2] Fault Analysis Group and Irish Centre for Research in Applied Geosciences (iCRAG), UCD School of Earth Sciences, University College Dublin, Dublin, Ireland

POSTER ABSTRACT

Borehole Heat Exchangers (BHE) in large Shallow Geothermal Energy (SGE) systems provide sustainable and low-carbon district heating solution for growing energy demand. In this study, an integrated numerical model of a Ground Source Heat Pump (GSHP) system was developed to optimize subsurface-to-surface thermal efficiency. The underground heat exchange process of BHEs was simulated using OpenGeoSys based on geological parameters from a potential development area at University College Dublin (UCD), while the surface segment employed TESPy (Thermal Engineering Systems in Python) to account for thermal demand and pipeline thermal-hydraulic balance. The system performance was evaluated through parametric analysis of BHE network, including the number, spacing, layout, and depth. Seasonal and long-term operational heat extraction patterns were further investigated to characterize system performance evolution, providing insight into quantifying thermal recharge and thermal interference effects between BHEs. An optimized design strategy for the GSHP configuration specifically tailored for the UCD potential development zone is proposed.

Keywords: *Shallow geothermal energy systems, borehole heat exchanger, OpenGeoSys, TESPy, thermal-hydraulic system optimization*

Design Optimization of Large-Scale Shallow Geothermal Systems for District Heating at UCD

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[2] Fault Analysis Group and Irish Centre for Research in Applied Geosciences (iCRAG), UCD School of Earth Sciences, University College Dublin, Dublin, Ireland

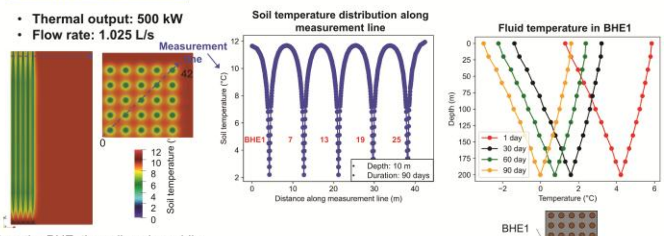
INTRODUCTION

Background: Shallow Geothermal Energy (SGE) systems represent a sustainable solution for meeting heating and cooling needs by using stable temperatures that below the ground surface. The systems rely on the efficient transfer of thermal energy between the ground and the surface, making them particularly suitable for a variety of climatic conditions. SEG provides a reliable alternative to traditional energy sources, contributing to reduced carbon emissions and enhanced energy efficiency.

Objectives: This study aims to develop and optimize a Borehole Heat Exchanger (BHE) network system for shallow geothermal energy at University College Dublin (UCD) by integrating site-specific geological and hydrogeological data with thermo-hydraulic simulations using OpenGeoSys and TESPy. Key factors—including BHE number, length, and groundwater flow—were analyzed to investigate subsurface heat transfer performance in the surrounding soil. Additionally, more realistic operational scenarios (such as a 12-hour daily cycle) were explored to achieve partial thermal recovery while fulfilling heating demands. This research seeks to ensure a stable thermal output (e.g., 500 kW) over extended periods, contributing to efficient, cost-effective, and environmentally responsible energy solutions at UCD.

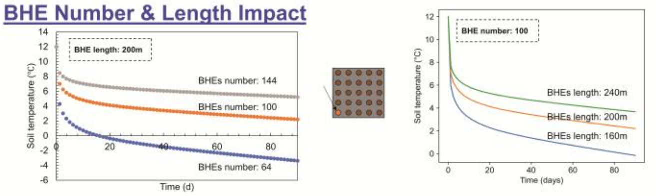
RESULTS

❑ Spatiotemporality



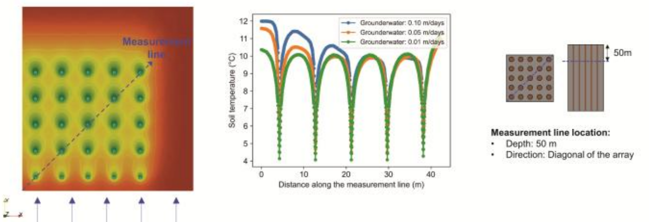
❑ Near the BHE, the soil cools rapidly.
❑ The water steadily gains heat, producing a V-shaped temperature profile with depth.

❑ BHE Number & Length Impact



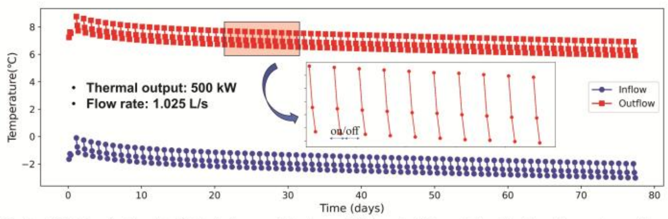
❑ Under a fixed heat demand (500kW), having more or longer BHEs maintains a higher surrounding soil temperature, indicating greater geothermal potential.

❑ Groundwater Impact



❑ Groundwater flow continuously replenishes heat, thereby enhancing the overall geothermal potential.

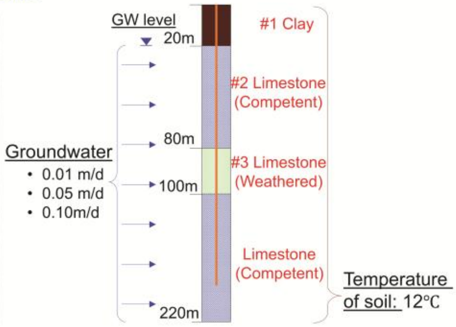
❑ 12-Hour Intermittent Geothermal Operation



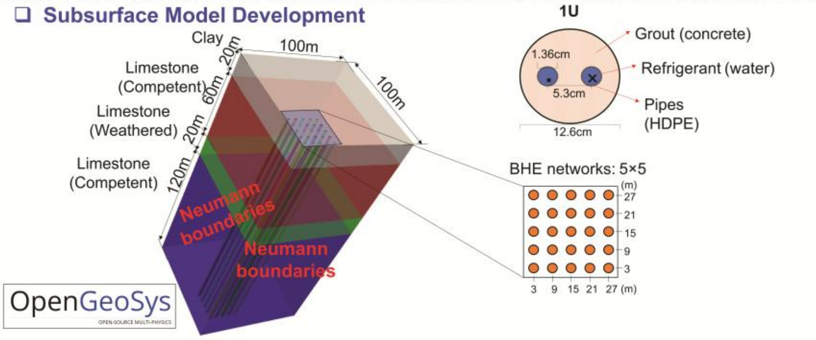
❑ Stable 500 kW output and 1.025 kg/s flow sustained over 80 days in 12-hour intermittent geothermal operation, confirming reliable cyclic performance.

METHODS

❑ Proposed Shallow Geothermal Site

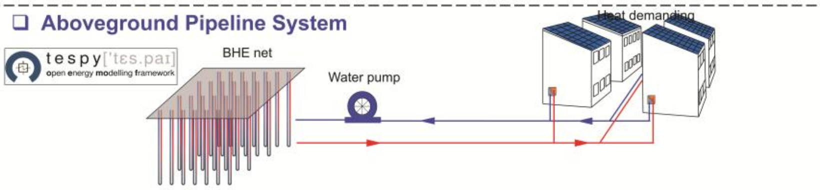


❑ Subsurface Model Development



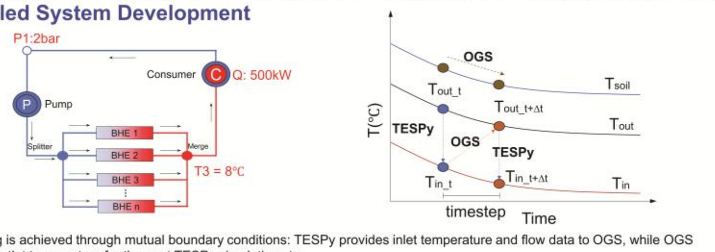
❑ **OGS** (OpenGeoSys) is an open-source simulator for THMC processes in porous media (used here to model heat transfer between BHEs and the surrounding soil).

❑ Aboveground Pipeline System



❑ **TESPy** (Thermal Engineering Systems in Python) is an open-source Python library for thermal energy systems (used here to simulate aboveground pipe flow, including pressure and temperature changes).

❑ Coupled System Development



❑ The coupling is achieved through mutual boundary conditions: TESPy provides inlet temperature and flow data to OGS, while OGS returns the outlet temperature for the next TESPy simulation step.

CONCLUSION

We developed a coupled thermo-hydraulic model by integrating OpenGeoSys (OGS) and TESPy to simulate a Borehole Heat Exchanger (BHE) network system for UCD, based on local geological and hydrogeological conditions.

❑ **SGE performance evaluation:** Subsurface temperature distribution is mainly affected by the number and depth of BHEs, groundwater flow, and operational mode. Increasing the number of BHEs (from 64 to 144) or depth (from 160 m to 240 m) reduces thermal depletion and maintains higher soil temperatures. Groundwater flow enhances lateral heat transport and improves heat extraction. Intermittent operation (12 h on / 12 h off) enables thermal recovery of the soil, increasing the long-term heat extraction potential.

❑ **Design optimization**: An optimized layout of 100 BHEs, each 200 m deep and spaced 6 m apart, is proposed. Under a 12-hour intermittent operation, the system sustained a stable thermal output of 500 kW over three months, with the surrounding soil temperature maintained at ~5.5 °C, confirming effective thermal recovery.

❑ **Ongoing work:** Current research focuses on evaluating economic feasibility and estimating CO_2 emission reductions under different heat source scenarios.

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ECOHYDROLOGICAL MONITORING OF TEMPERATE RAISED BOGS USING C-BAND SAR

Mahdi Khoshlahjeh Azar[1,2], Alexis Hrysiewicz[1,2], Shane Donohue[2,3], Shane Regan[4], Raymond Flynn[5], Florence Renou-Wilson[6], Eoin Reddin[7], Mark G. Healy[7], & Eoghan P. Holohan[1,2]

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Ecohydrological Monitoring of Temperate Raised Bogs Using Satellite C-Band SAR

Mahdi Khoshlahjeh Azar[1,2], Alexis Hrysiewicz[1,2], Shane Donohue[2,3], Shane Regan[4], Raymond Flynn[5], Florence Renou-Wilson[6], Eoin Reddin[7], Mark G. Healy[7], & Eoghan P. Holohan[1,2]

iCRAG RESEARCH IRELAND CENTRE FOR APPLIED GEOSCIENCES

1. Problem Statement

Peatland degradation promotes carbon emissions, biodiversity loss, water quality decline, and slope instability.

Effective mitigation of these impacts depends on **understanding and monitoring peatland ecohydrology across space and time**.

Problems:

(1) Large scales require remote monitoring (Fig. 1) (regional, national, or global).

(2) Cloud cover inhibits regular imaging by optical or multispectral satellites.

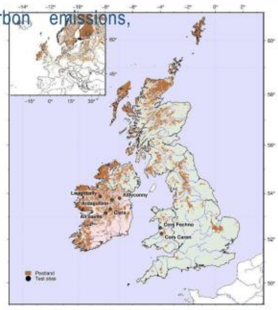

Fig.1: Distribution of peatlands in Ireland and Britain

2. Synthetic-Aperture Radar Remote Sensing

Synthetic-Aperture Radar (SAR) imaging is an active remote sensing approach **that can penetrate clouds** (Fig. 2), thus overcoming limitations of optical imaging in the temperate Irish climate.

$$\sigma^0 = f(\varepsilon_r, s, \lambda, \theta_i, P)$$

Eq.1. RADAR Backscattering Equation

ε_r = Relative dielectric constant
s = Surface roughness
λ = Radar wavelength
θ_i = Incidence angle
P = Polarization

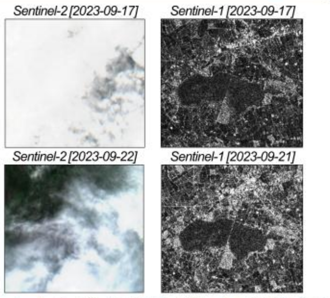

Fig.2: Examples of optical (Sentinel-2 Natural Colour) and SAR (Sentinel-1 intensity) images over Clara Bog acquired on the same dates.

3. Study Areas

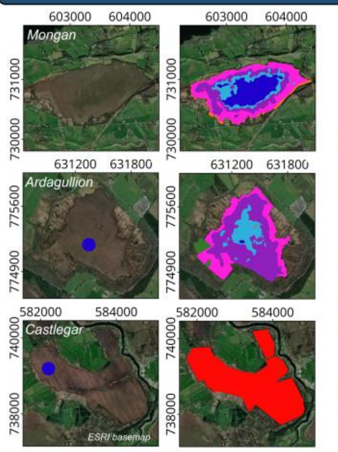

Fig.3: Study sites with relevant Ecotopes from NPWS. Blue points indicate piezometer locations for data in Fig XX and Fig XY.

Mongan: largely intact, with high coverage of ***sphagnum moss-dominated central, and sub-central ecotopes*** (Fig. 3).

Ardagullion: degraded, with mainly bushy ***heather-dominated marginal and sub-marginal ecotopes***. Under restoration since 2019.

Castlegar: industrially harvested, ***primarily bare peat***. Under restoration since 2022.

4. Temporal Analysis of SAR Backscatter Intensity

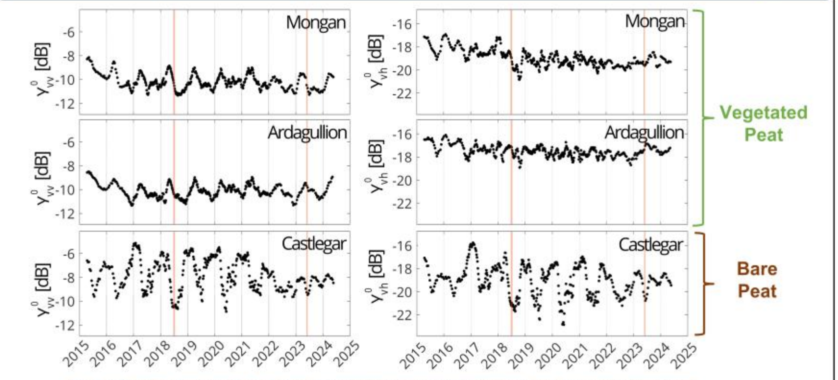

Fig.4: SAR intensity time series for study sites: VV polarization (left) and VH polarization (right). VV = vertical transmit and vertical receive; VH = vertical transmit and horizontal receive. Vertical orange bars denote drought periods.

- SAR intensity oscillates annually; greater in winter, lower in summer (Fig. 4). Compared to bare peat, vegetated bogs show both a lower oscillation amplitude and a lower average intensity.

5. Spatial Analysis of SAR Backscatter Intensity

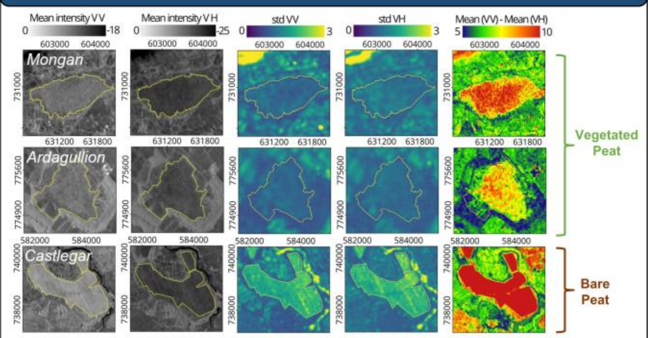

Fig.5: Maps of mean and standard deviation of SAR intensity in VV and VH polarizations (2015–2024), as well as the difference between mean intensity in the VV and VH polarizations.

- The vegetated bogs thus appear darker in SAR imagery (lower mean intensity and lower standard deviation) (Fig. 5). The bare peat is brighter (higher mean intensity; and standard deviation) and has greater difference in mean intensity.

6. Relationship between SAR Intensity and Ecology

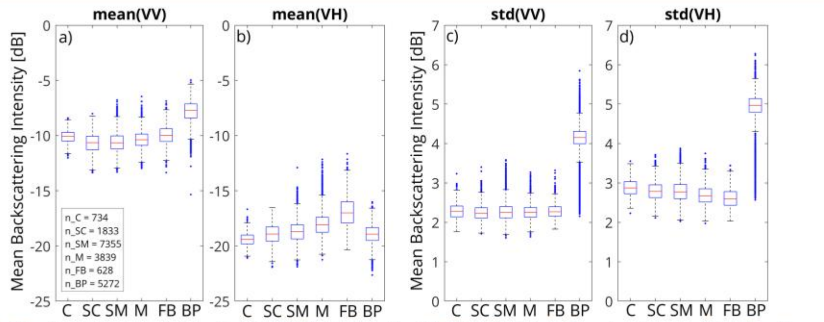

Fig.6: Boxplots showing mean and standard deviation of SAR backscattering intensity in VV and VH polarizations for each ecotope across all bogs (C=central; SC=sub-central; SM=sub-marginal; M=marginal; FB=face bank; BP=bare peat - see Fig. 3).

- Low mean VV values in vegetated peat (Fig. 6) relate to attenuation by vegetation. Increased mean VH with denser/bushier vegetation is linked to greater volumetric backscattering. Bare peat is generally brighter in VV (no signal attenuation), but more variable (higher standard deviation - due to greater soil wetting and drying).

7. Relationship between SAR Intensity and Groundwater Level

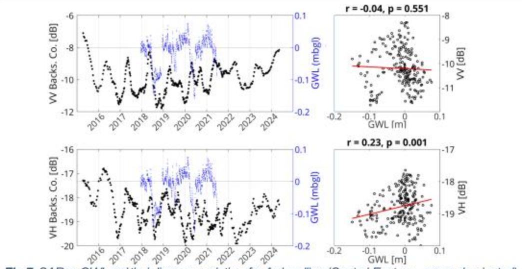

Fig.7: SAR vs. GWL and their linear correlation for Ardagullion (Central Ecotope - moss-dominated)

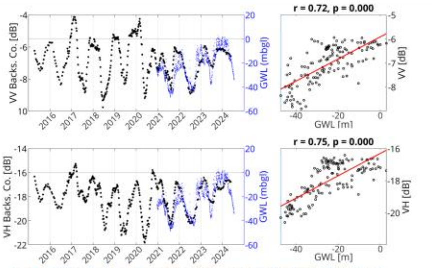

Fig.8: SAR vs. GWL and their linear correlation for Castlegar (Bare Peat)

- Groundwater level (GWL) and SAR intensity are poorly correlated for vegetated peat (Fig. 7), and so SAR intensity as a proxy for estimating absolute GWL is not straightforward. GWL and SAR intensity are well correlated for bare peat, however (Fig. 8).

8. Conclusions

- The annual oscillation in SAR intensity displays a strong correlation with groundwater levels where vegetation coverage is limited. However further analysis and investigation are required to monitor groundwater fluctuations using SAR in high bog areas.
- The higher mean VV intensity of bare peat is due to the minimal attenuation of the SAR pulse by vegetation. In contrast, the sensitivity of mean VH intensity to vegetation type is explained by increased volumetric scattering of radar waves in shrub-rich areas.
- Spatio-temporal variations in SAR backscatter signatures can therefore serve as valuable indicators for identifying and monitoring human impacts on temperate raised bogs.

This presentation has emanated from research financially supported by Taighde Éireann – Research Ireland, under Grant Number 13/RC/2092_P2 at the iCRAG Research Ireland Centre for Applied Geosciences.

Taighde Éireann Research Ireland

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Details of the 2024-2025 Bursary Scheme will be circulated after the conference.

Talamhireland
Dr. Robert Meehan

TOBIN
CONSULTING ENGINEERS
Coran Kelly

David Ball

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