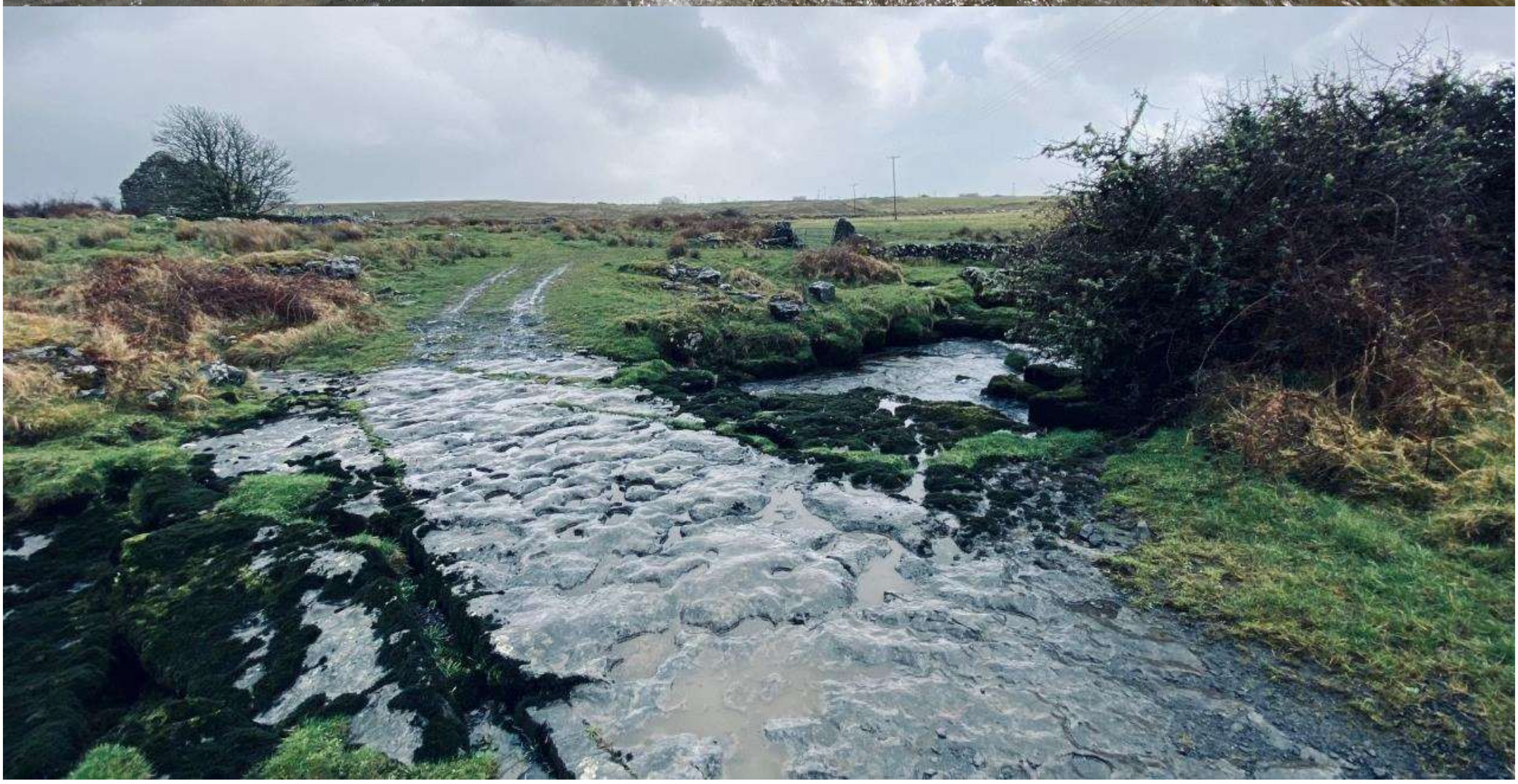

Groundwater: Making the Invisible Visible

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS - Irish Group

Proceedings of the 42nd Annual Groundwater Conference

Online, 26th and 27th April 2022

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

Presents

Groundwater:
Making the Invisible Visible

Proceedings of the 42nd Annual Groundwater Conference

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INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH GROUP)

Introduction

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

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

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

The IAH (Irish Group) is also a sponsoring body of the Institute of Geologists of Ireland (IGI).

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

2022 IAH (Irish Group) Conference **Groundwater: Making the Invisible Visible**

It gives me great pleasure, on behalf of all of us on the organising committee, to welcome you to the 42nd annual IAH Irish Group Conference. Your continued involvement and support of the IAH Irish Chapter is invaluable.

As with last year, we are running the entire meeting online, using the same format from 2021: two half-days with short presentations from early career hydrogeologists. The main sessions will each be followed by live Q&A, and questions can be submitted by attendees through Zoom.

The theme of the conference this year is *Groundwater: Making the Invisible Visible*. This not only follows the main theme of World Water Day 2022 but also allows us as practitioners to think about how we talk about groundwater. *Groundwater is invisible, but its impact is visible everywhere. Out of sight, under our feet, groundwater is a hidden treasure that enriches our lives, it is the source of springs, wells and many rivers. As climate change impacts become more acute, groundwater resources will become more and more critical, are we doing enough to plan for potential eventualities?**

On our first day, session one, *Exploring Groundwater*, will take a broader perspective and includes talks on the role of groundwater in the 2022 UN World Water Development Report (Michaela Miletto, UNESOC WWAP), on Ireland's geothermal potential (Sarah Blake, GSI) and how structure influences groundwater movement and storage (Pat Meere, UCC). Session two, *Groundwater Resource Resilience*, gets underway with an overview of groundwater in the World Water Quality Alliance (Claudia Ruz Vargas, UN IGRAC), updates to the Irish National Karst database (Caoimhe Hickey, GSI), how groundwater is being incorporated into public supplies in Northern Ireland (Paul Wilson, GSNI), and updates on two GSI programmes that focus on groundwater (Katie Tedd, GSI).

Half-day number two kicks off with a session on *Communication*, with talks on how to use groundwater in geoscience communication (Kirstin Lemon, GSNI), the broader experiences of communicating geoscience to the public (Fegus McAuliffe, iCRAG), and how to foster and support community engagement (Donal O'Keefe, LAWPRO). The final session considers *Emerging Issues in Groundwater*, and the speakers will talk about their research on using passive seismic methods to listen to water flowing in conduits (Haleh Karbala Ali, DIAS), groundwater contaminants of emerging concern (Dan Lapworth, BGS), and a linked presentation on the global and Irish perspective on PFAS in groundwater (Olivia Hall & Ian Ross, TetraTech). The final presentation will consider Irish Holy Wells (Bruce Misstear, TCD).

Following the conference, we will be sending out a survey to all registrants and we are keen to hear your feedback, thoughts, ideas and suggestions.

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

Tiernan Henry
IAH (Irish Group)
Conference Secretary

* www.worldwaterday.org/

2022 IAH (Irish Group) Committee:

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

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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:

Talamhireland

Dr. Robert Meehan

‘Groundwater: Making the Invisible Visible’

International Association of Hydrogeologists – Irish Group
42nd Annual Groundwater Conference – Online Event
Tuesday 26th April – Wednesday 27th April 2022

Programme Day 1, Tuesday 26th April

13.00 *Conference Login Open*

SESSION I: Exploring Groundwater

13:30 Welcome & Introduction -Tiernan Henry (NUIG), Conference Secretary, IAH (Irish Group)

13:40 **Richard Connor** (UNESCO WWAP): *Making visible the invisible groundwater resource: the 2022 UN World Water Development Report.*

14:00 **Sarah Blake** (GSI*): Ireland's Geothermal Potential: data from Grangegorman, Dublin City*.

14:20 **Pat Meere** (UCC): *Structural Controls on Fluid Flow in the Munster Basin, Southern Ireland.*

14:40 Q&A

15:00 **Early Career One-Minute Poster Presentations**

Introduction & Chair: Lindsay Connolly (ARUP)

15:20 Break

SESSION II: Groundwater Resource Resilience

15:35 Introduction

15:40 **Claudia Ruz Vargas** (UN IGRAC): *The Role of Groundwater in the World Water Quality Alliance.*

16:00 **Caoimhe Hickey** (GSI): *Revealing the Invisible: Geological Survey Ireland's National Karst Database*.

16:20 **Paul Wilson** (GSNI): *Bringing Groundwater Back into Public Supply.*

16:40 **Katie Tedd & Ted McCormack** (GSI): *Improving the understanding of current and future groundwater resources: GW3D and GWClimate.*

17:00 Q & A

17:30 End of Day 1

Programme Day 2, Wednesday 27th April

09:00 *Conference Login Open*

SESSION III: Communication

09:30 Introduction

09:35 **Kirstin Lemon** (GSNI): *Creating Lightbulb Moments: the Power of Using Groundwater in Geoscience Communication.*

09:55 **Fergus McAuliffe** (iCRAG): *Geoscience Communication.*

10:15 **Donal O'Keefe** (LAWPRO): *Evolving Community Engagement.*

10:35 Q&A

11:00 Break

SESSION IV: Emerging Issues in Groundwater

11:15 Introduction

11:20 **Haleh Karbala Ali** (DIAS): *Locating Flowing Conduits in Karst using Passive Seismic Approach.*

11:40 **Dan Lapworth** (BGS): *Groundwater Contaminants of Emerging Concern.*

12:00 **Olivia Hall & Ian Ross** (TetraTech): *Poly- and Perfluoroalkyl Substances (PFAS) in Groundwater: a global & Irish perspective.*

12:20 **Bruce Misstear** (TCD): *Irish Holy Wells: their Groundwater Sources, Water Chemistries & Healing Reputations.*

12:40 Q & A

13:10 Closing Address – Gerry Baker (ARUP), President, IAH (Irish Group)

13:20 **End of conference**

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SESSION IV: Emerging Issues in Groundwater

SESSION I

MAKING INVISIBLE GROUNDWATER RESOURCES VISIBLE: THE UN WORLD WATER DEVELOPMENT REPORT

Richard Connor, *UNESCO World Water Assessment Programme, Perugia (It)*

ABSTRACT

The 2022 edition of the United Nations World Water Development Report describes the challenges and opportunities associated with the development, management and governance of groundwater across the world.

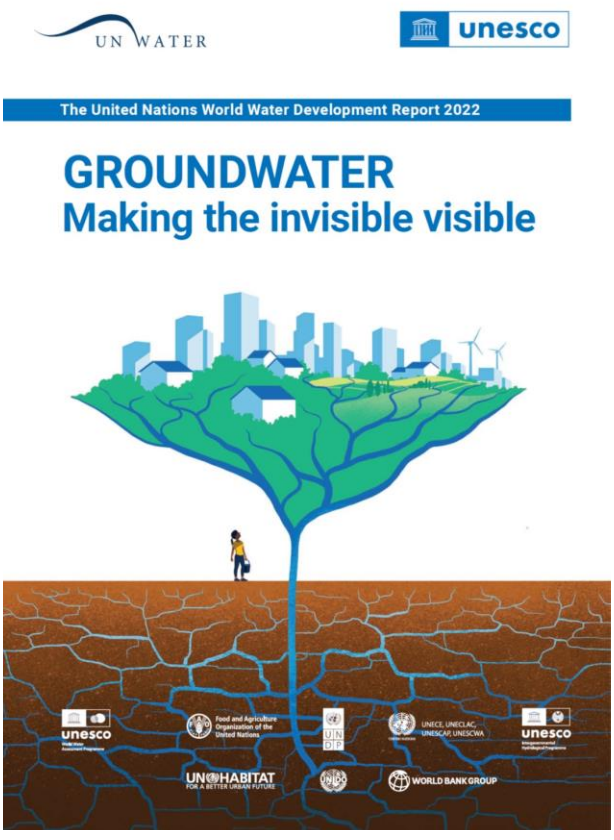
Accounting for approximately 99% of all liquid freshwater on Earth, groundwater has the potential to provide societies with tremendous social, economic and environmental benefits and opportunities. Groundwater already provides half of the volume of water withdrawn for domestic use by the global population, including the drinking water for the vast majority of the rural population who do not get their water delivered to them via public or private supply systems, and around 25% of all water withdrawn for irrigation.

However, this natural resource is often poorly understood, and consequently undervalued, mismanaged and even abused. In the context of growing water scarcity across many parts of the world, the vast potential of groundwater and the need to manage it carefully can no longer be overlooked.

Key words: *Groundwater, WWDR*

Full report available for download here:

https://www.unwater.org/publications/un-world-water-development-report-2022/#:~:text=The%202022%20edition%20of%20the,of%20groundwater%20across%20the%20world.



IRELAND'S GEOTHERMAL POTENTIAL: DATA FROM GRANGEGORMAN, DUBLIN CITY

Dr Sarah Blake, *Groundwater & Geothermal Unit, Geological Survey Ireland, Block 1, Booterstown Hall, Booterstown, Blackrock, Co Dublin, A94 N2R6.*

ABSTRACT

Through the provision of high-quality geothermal data and products, Geological Survey Ireland are currently working to remove some of the barriers to deployment faced by geothermal energy projects, at both small and large scales. Our ambition in this next decade is to help realise the first deep geothermal district heating demonstration project in Ireland and support the development of an indigenous geothermal industry. To this end, Geological Survey Ireland have partnered with Technological University Dublin (TUD) to explore the geothermal resource beneath the TUD Grangegorman campus in Dublin 7. In late 2021 an exploratory corehole was drilled by Geological Survey Ireland at Grangegorman to a depth of 998 m, and a local average geothermal gradient of 28 ˚C/km was established. The information from this hole will be used to plan and budget for a deep geothermal installation at the same location. A successful geothermal district heating pilot scheme will prove the technology in Ireland and pave the way for further projects to fulfil geothermal energy's potential in Ireland's energy transition.

Key words: *Geothermal energy*, *geothermal gradient, district heating, Dublin Basin, stratigraphy, decarbonisation of heat*

INTRODUCTION

Founded in 1845, Geological Survey Ireland is Ireland's public earth science knowledge centre and is a division of the Department of the Environment, Climate and Communications (DECC). Geological Survey Ireland has supported geothermal projects in Ireland since the early 1980s, and geothermal research has been a core programme activity of our Groundwater & Geothermal Unit for over a decade. We collect and collate geothermal data to produce maps, reports, and user guides on Irish geothermal resources, and provide impartial scientific advice to policy makers and the public.

Geothermal energy is a secure, environmentally sustainable, and cost-effective source of renewable energy commonly used across the globe to heat and cool homes and businesses, as well as in industrial and agricultural applications. It is currently enjoying a period of renewed interest and support across the EU in response to ever-increasing pressure to decarbonise our energy systems and improve the security of our energy supplies. Technological advances in recent decades have placed deep geothermal heat and electricity within reach in many "low-enthalpy" (or low-temperature) locations across the EU, including in Ireland.

The EU defines geothermal energy as "energy stored in the form of heat beneath the surface of solid Earth" – this definition covers everything from heat stored in the soil and subsoil, to high temperature resources many kilometres beneath the Earth's surface. In general, heat flows outwards from the centre of the Earth, and the temperature (and the amount of available energy) increases with depth at an average rate of 25 to 30 °C per kilometre for most places in the world. Geothermal energy is practically zero-carbon at source, and whilst

Ireland does not have a 'traditional' geothermal setting (i.e., we are situated far from active volcanoes), geothermal energy could be a viable, significant source of energy in Ireland particularly for heating and cooling homes and businesses, district heating and the agri-food sector.

Barriers
Lack of public interest/support for GT
No "proof of concept" in Ireland (deep)
Lack of funding for demonstrator projects
Lack of regulatory framework
Lack of subsurface knowledge

Figure 1*: Identified barriers to large-scale deployment of geothermal projects in Ireland.*

Geological Survey Ireland has identified five main barriers (Figure 1) to the large-scale deployment of geothermal energy projects in Ireland (GSI, 2020). DECC and Geological Survey Ireland are committed to addressing these barriers and encouraging the uptake of low-carbon geothermal energy and the development of our geothermal industry; this activity has largely been driven by the Climate Action Plans to date. Geological Survey Ireland have contributed technical advice to the development of DECC's 2021 Draft Policy Statement on Geothermal Energy for a Circular Economy, and DECC will develop dedicated legislation and a regulatory framework for geothermal energy over the next several years.

Geothermal developments in Ireland are currently hampered by a lack of relevant subsurface data, which compounds the overall financial risk of a geothermal project and may contribute to lack of understanding and acceptance from the public. Geological Survey Ireland are developing a new end-user-focussed National Geothermal Database to support the Department's geothermal goals by providing essential geothermal information about Irish rock types. We also continue to regularly fund geothermal energy research through national and international consortia. This new information will enable accurate assessment of the geothermal resources available and help to bridge the existing knowledge gaps about our deep subsurface geology.

DECARBONISING OUR HEAT SECTOR

The Irish heat sector is our most problematic in terms of carbon emissions and has proved the hardest to decarbonise. We generate approximately 40% of our carbon emissions by using fossil fuels to heat our homes, buildings, and businesses (SEAI, 2022). Ireland currently has the lowest share of renewable heat (RES-H) in the EU at just 6.3 % (Eurostat, 2022), and this is a key factor in our poor performance towards our renewable energy targets. The recently published National Heat Study (SEAI, 2022) has highlighted that existing policy measures are insufficient to meet our 2030 target of a 51% reduction in emissions.

Geothermal energy is a renewable, low-to-zero carbon resource. By tapping into our national geothermal energy resources for a range of applications (Figure 2), we will replace some of these fossil fuels with a secure and sustainable heating alternative, whilst also increasing our RES-H and reducing emissions. District heating networks are common throughout Europe and have been recognised as the best way to decarbonise the heat sector where the heat demand, or population density, is high (Connolly et al., 2015). Geothermal energy can be used on its own or as part of a mix of energy sources in district heating schemes. The National Heat Study (SEAI, 2022) sets out the need for rapid deployment of district heating in Ireland and recognises geothermal energy as a significant potential source for these networks, whilst also highlighting the following: "*Further work aimed at the complete characterisation of the suitability of the geothermal resource across Ireland will allow a better understanding of its potential for district heating at various locations*".

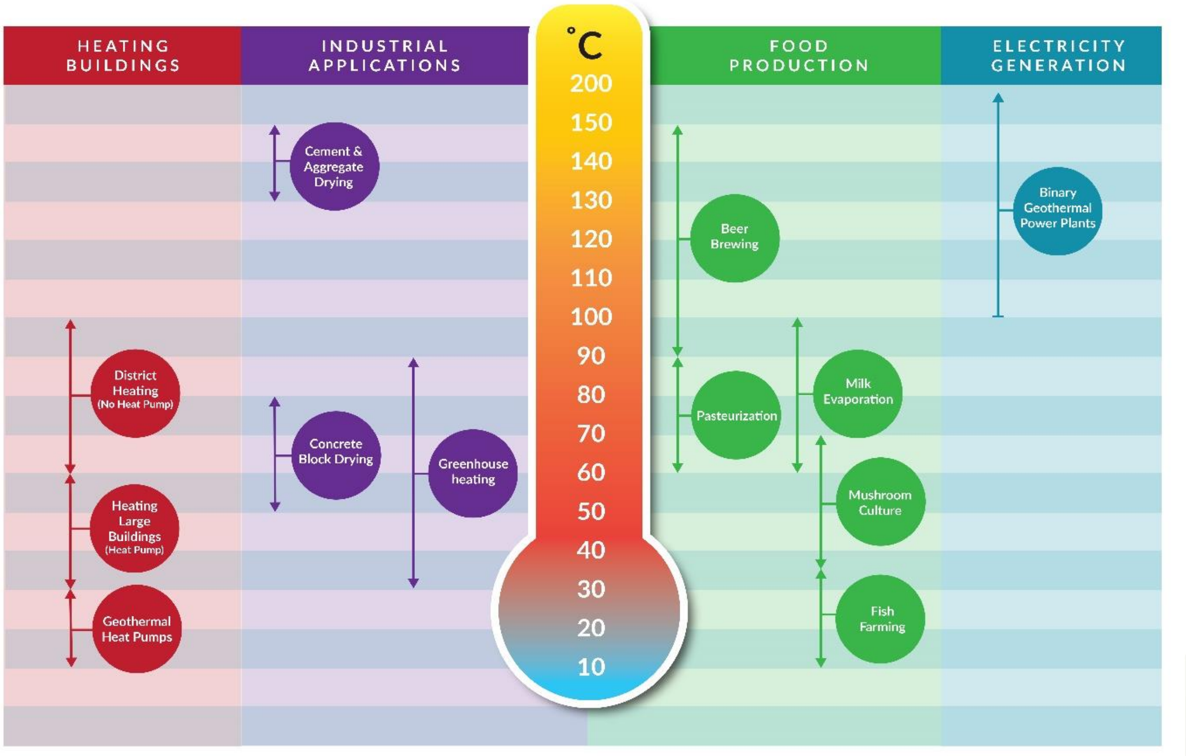


***Figure 2**: Irish geothermal resources could be used for a wide variety of heating and cooling applications (GSI, 2021a).*

An increase in the number and scale of geothermal district heating systems for municipal buildings is achievable in Ireland. There are many examples in Ireland of individual municipal buildings connected to shallow geothermal ground source heat pump systems (GSHPs). However, increasing capacity through deeper and larger scale geothermal installations is possible. For example, the geothermal system installed in Orly Airport in the Île-de-France region provides heating and hot water through a 35 km heating network at the airport campus. It was built between 2008 and 2011 and includes a 1.8 km geothermal doublet (pair of wells) that cost €9M to drill. The installed capacity of the entire network is approximately 135 MW_{th} (incorporating heat pumps and a biomass boiler) and it is estimated that the system has reduced emissions by 8,200-9,000 tons of CO_2 per year compared to the equivalent fossil fuel heat sources (GeoDH, 2014).

IRELAND'S GEOTHERMAL RESOURCES

Ireland's geothermal energy resources are currently under-utilised and mostly used for small-scale, individual heating projects (e.g., for single domestic dwellings or industrial heating applications). Our low-temperature, shallow resources have been well documented by Geological Survey Ireland in a series of geothermal suitability maps and an accompanying Homeowner's Guide to Ground Source Heat (GSI, 2015). GSHP technology is market-ready and highly scalable, and hence has the potential to have a significant decarbonising impact. However, the sector will require targeted policy measures to grow. In contrast to other ambient source heat pump systems, GSHPs can provide heating, cooling and thermal storage and offer higher efficiency due to the stable ground/groundwater temperatures all year round. Collection of high-quality data will be important for subsurface management and environmental monitoring as the installed capacity of GSHPs increases, particularly in urban areas or areas where there are competing uses of the subsurface.

Ireland's deep geothermal resources are poorly understood at present. To facilitate geothermal energy development, further geological research is needed to estimate potential geothermal resources (flow rates, temperatures, rock properties, and generally improved subsurface and structural characterisation) through programmes including geological studies, geophysics, and drilling. The careful treatment of sparse existing legacy data can be useful, as well as the development of new methodologies for modelling the deep subsurface. Geological Survey Ireland released a new suite of deep temperature maps in 2021 (Figure 3). These maps were developed using data from a 3D thermal model of the crust beneath Ireland. This model was constructed using lithospheric scale geophysical data (Mather et al., 2019) and demonstrates the relative enhanced deep geothermal potential of the southeast, southwest, and north of the island.

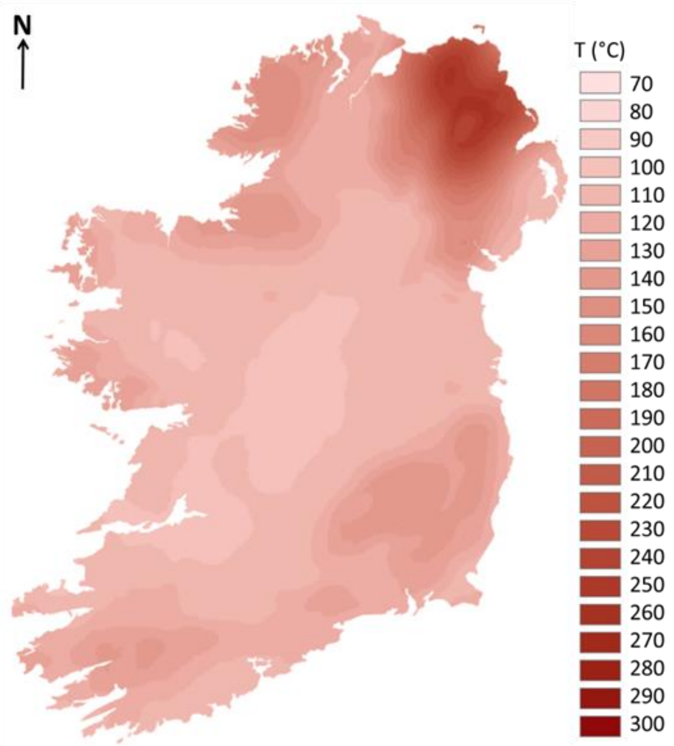


Figure 3*: Deep temperature map of Ireland at a depth of 3 km based on a probabilistic joint inversion of geophysical data (GSI, 2021b; based on thermal model by Mather et al. (2019)). Temperatures in degrees Celsius range from 90 °C to 260 °C.*

GEOTHERMAL EXPLORATION AT TUD GRANGEGORMAN

Geothermal energy has long been linked to the development of district heating in Ireland, as the traditionally centralised heat source and long-term nature of these projects make them a natural fit for deep geothermal developments (modern district heating systems also combine lower input temperatures with a mix of renewable heat sources, which makes them even more compatible with geothermal heat). In the absence of appropriate financial and regulatory conditions, public investment is critical to realise geothermal district heating in Ireland, to raise awareness of Irish geothermal resources and demonstrate proof of concept here.

The Technological University Dublin (TUD) campus at Grangegorman has been identified as a suitable candidate for a deep geothermal pilot project, due to its central location in the

Dublin Basin, and existing district heating infrastructure. An exploratory test borehole was planned for Grangegorman with the aims of: i) drilling vertically for 1 km, ii) collecting 1 km of bedrock core samples, iii) accurately measuring the temperature profile and geothermal gradient to a depth of 1 km, and iv) collection of downhole geophysical data. This information will be used to help us understand more about the geothermal conditions at Grangegorman and in the Dublin Basin, and assist with planning future geothermal wells in the area.

With the help of TUD, a site adjacent to the Grangegorman Energy Centre was identified and prepared for drilling. Works commenced in July 2021 and the borehole was completed in November 2021 (total cumulative drilling time of around 12 weeks). The final temperature measurements were filmed by RTÉ on the 22nd of November (and featured in an RTÉ EcoEye episode on decarbonisation of heat, aired on February 8th 2022). Specialist contractors were procured by Geological Survey Ireland to log downhole with geophysical equipment (one week on site).

The following data sets were collected:

- Drillers logs,
- 998 m of core samples (NQ diameter),
- Distributed temperature profile (fibre optic method),
- Detailed stratigraphic log,
- Fracture log,
- Downhole wireline geophysics, and
- Experimental seismic data acquired by DIAS during drilling.

HYDROGEOLOGICAL SUMMARY

The following notes were compiled from the driller's notes and the stratigraphic log of the core (carried out by our Geological Mapping Unit). The bedrock was found to be typical of the Carboniferous limestone succession of this part of the Dublin Basin (Lucan Fm. to 659 m below ground level (mbgl), Tober Colleen Fm. to 900 mbgl, Boston Hill Fm. with proximal Waulsortian reef facies to end of hole). First water strike occurred at around 10 mbgl and rockhead was encountered at 17 mbgl. Some intensely fractured horizons were encountered at around 170, 370 and 500 mbgl. Partial losses were reported between 210 and 225 mbgl and another water strike occurred in a fractured horizon at 460 mbgl. From 510 mbgl until the end of the hole the rock was remarkably competent aside from one interval of porous dolomite at 833 to 845 mbgl (there was a significant artesian water strike at this level). Zebra dolomite was encountered between 935 and 947 mbgl.

TEMPERATURE PROFILE

Geological Survey Ireland has a fibre optic Distributed Temperature Sensor (DTS) equipped with reinforced cable specifically designed to measure temperatures downhole. This provides a continuous temperature profile along the entire length of the cable. Unfortunately, the temperature measurements had to be taken inside the rods due to instability in the hole. (The hole later collapsed during wireline logging with the loss of a tool, so repeat measurements were not possible.) The DTS was deployed on 22nd November six days after drilling ceased (the hole was not flushed during this period). The resulting temperature profile can be seen in Figure 4. A temperature of 38 ˚C was recorded at 998 m below surface (averaged from 12 measurements) giving a local average geothermal gradient of 28 ˚C/km. No correction has been applied to the temperature measurements.

CONCLUSIONS

The geothermal gradient at Grangegorman is promising and demonstrates the potential of the geothermal resource beneath TUD and Dublin City. If source temperatures of greater than 60°C can be achieved, the district heating system may not require a heat pump as the water extracted is already at a usable temperature (Codema, 2019). A reservoir temperature of 80 ˚C is currently targeted, and this will require drilling to a depth of at least 2.5 km. Permeability and geological structures at depth are uncertain, and a geophysical survey is planned to help target the drilling. A full well design and specification exercise using the detailed geological information collected in 2021 is currently underway. This is needed to accurately estimate the cost of a functional geothermal well at Grangegorman. In mid-2022 Geological Survey Ireland, TUD and a broader consortium in Ireland and Northern Ireland will apply for funding for a geothermal demonstration project at Grangegorman. A successful geothermal district heating pilot at Grangegorman will prove the technology in Ireland and pave the way for further projects to fulfil geothermal's potential in Ireland's energy transition.

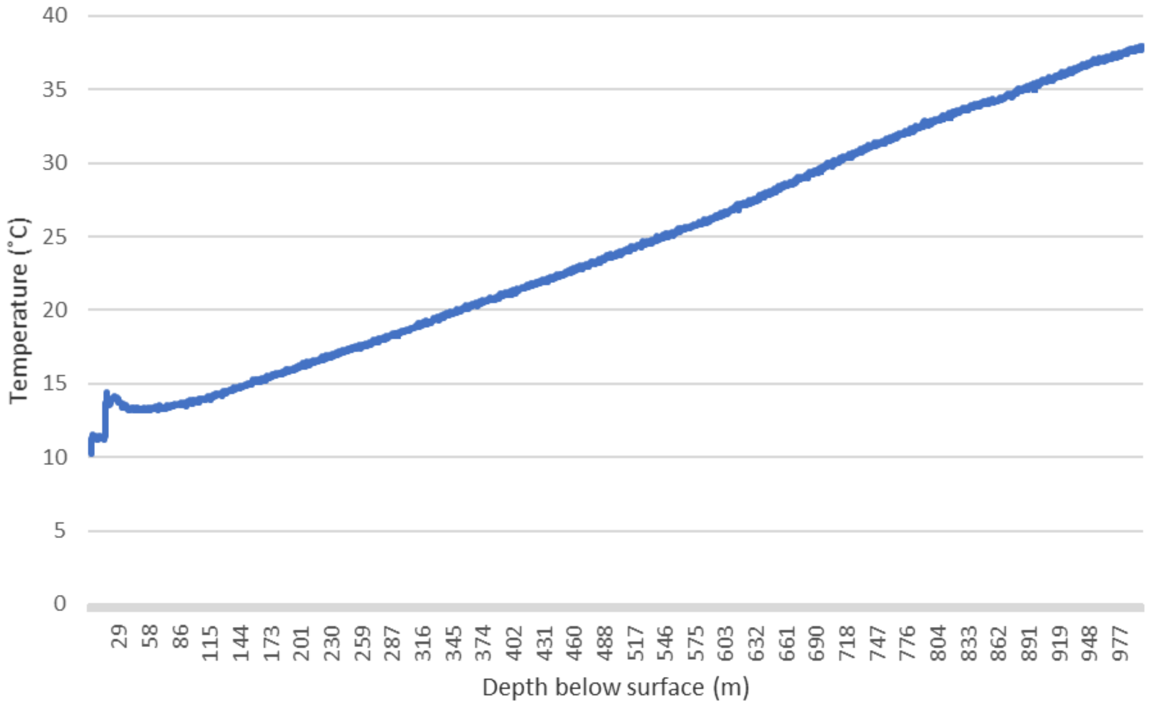


Figure 4*: Temperature profile from Grangegorman. Maximum temperature of 38 ˚C (uncorrected) recorded at a depth of 998 m.*

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Pre-Variscan (Extensional) and Variscan Faulting in the Allihies Mining Area, Southwest Ireland – A New Structural and Chronological Evaluation

Patrick A. Meere[1], Jürgen Lang[1]*, Richard P. Unitt[1], Sean C. Johnson[2], Koen Torremans[2] & David Selby[3]

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3 Department of Earth Sciences, University of Durham, Durham, United Kingdom

INTRODUCTION

Between the Middle and early Upper Devonian, north-south crustal extension led to the development of a half-graben structure in southern Ireland that comprises the Munster Basin (Naylor & Jones 1967). The northern bounding structure of this intracratonic basin has been described as the east-west trending, listric Coomnacronia-Killarney-Mallow Fault Zone (Price & Todd, 1988; Meere 1995; Landes *et al.* 2003; Ennis *et al.* 2015) or the Dingle Bay-Galtee Fault Zone (Williams *et al.* 2000). Late Middle to Upper Devonian alluvial and fluvial siliciclastic sediments derived mainly from the north were transported into the Munster Basin (MacCarthy, 1990). These 'Upper Old Red Sandstone' sediments formed a basinal infill of over 6 km (Meere & Banks 1997).

Towards the end of the Devonian the formation of another east-west trending fault system, the Cork-Kenmare Fault Zone resulted in continuous subsidence of the South Munster Basin (MacCarthy, 2007). This was accompanied by a marine transgression from the south with resulting accumulation of marine siliciclastic within the South Munster Basin and limestones on a more stable platform to the north (MacCarthy, 2007).

At the end of the Carboniferous NNW-directed compression terminated sedimentation in the region and marked the beginning of the Variscan Orogeny (Sanderson 1984; Meere 1995b;

Quinn *et al.* 2005). Bulk shortening of over 52% was achieved by pervasive cleavage development followed by kilometre scale buckling and faulting. This resulted in the reactivation of high-angle basin-controlling faults. In the west of the Munster Basin, Meere (1995c) identified NE-SW-trending reverse faults, as well as rarer NW-SE-trending strike slip faults. The sediments underwent metamorphism to sub-greenschist facies (Meere 1995b).

ALLIHIES STRUCTURAL SETTING

The Allihies Mining District is located near the western end of the Beara Peninsula. The predominant lithologies are purple and green siltstones and sandstones of the Caha Mountain Formation (MacCarthy *et al.* 2002). The Caha Mountain Formation can be subdivided into the Allihies Sandstone Member, which mainly outcrops north of Mountain Mine (Fig. 3.2) and has an approximate thickness of 1200 m, and the underlying Ballydonegan Slate Member (south of Mountain Mine) that has an approximate thickness of 1500 m (Reilly 1986).The Allihies copper mines are positioned on the northern limb of the Beara Anticline (Sheridan 1964). Around the mines, third order open symmetrical folds with wavelengths of 90 to 150 m, trending SW-NE can be found associated with fault zones following similar strike (Reilly, 1986). Penetrative cleavage is sub-vertical and strikes SW-NE.

There has been differing opinions about the timing of the vein structures and the copper mineralization of the Allihies region. For example, mineralized veins were considered to post-date the barren veins and Variscan compression tectonics (Sheridan 1964). In direct contrast is the observation by Sanderson (1984) that mineralized (chalcopyrite and siderite) N-S trending quartz veins are both strongly folded and cleaved, suggesting a pre/syn-Variscan age. Sanderson (1984) also proposed that the east-west veins, which include the main lodes of the mining area, were formed in association with the cleavage development and the folding. Wen *et al.* (1996) and Spinks *et al.* (2016) suggested remobilisation of sediment-hosted sulphides into late- or post-Variscan quartz veins.

PRE-VARISCAN FAULTING

East-West striking, normal faults with a strike-length of 60 to over 1000 m are present near, and at, the historic mine shafts. Sub-parallel to ESE-WNW striking quartz veins occur up to 35 m from the E-W faults. These veins are mineralized and range from centimetre to metre scale in diameter and have a maximum length of over 100 m. Only two vein sets have been observed striking North-South, including the N-S Lode at Mountain Mine.

VARISCAN DEFORMATION

Early cleavage development was associated with significant layer parallel shortening (LPS). Penetrative cleavage is clearly visible within the siltstones, but less distinctive within the sandstones. This cleavage (S_1) has a general SW-NE strike with a sub-vertical. Most of the early quartz veins (e.g. at Great Mountain Mine North and Coom Mine) show clear evidence of syn-compressional cleavage development, S_1 cleavage-refraction in the veins compared to the surrounding siltstones and cataclastic deformation. Smaller E-W veins sometimes display asymmetric folding, cleavage and boudinage. Cleavage development was followed by regional folding on all scales from the 1st order regional Beara Anticline to second and third order step folds show bedding-S_1-cleavage intersection lineations with a mean plunge of 47 degrees to the southwest. Large scale SW-NE trending strike slip faults result in predominantly sinistral offset of the E-W faults with a maximum dislocation of 17 m observed near the New E-W Lode. SE-NW to SSE-NNW striking faults (e.g. Cornish Village Fault constrain the northern and southern boundaries of the fault blocks (Fig. 1). All ESE-WNW trending veins are affected by oblique faulting with lateral sinistral offsets of up to 83m. Metre-scale joints observed are generally oriented SE-NW with a sub-vertical.

FLUID PHASE PETROLOGY

Quartz vein samples for fluid inclusion microthermometry were classified into 11 extensional (Pre-Variscan) E-W veins, and two syn-compressional (Syn-Variscan, saddle reef and en echelon) vein samples. Eight of the extensional (Pre-Variscan) samples are mainly mineralized with chalcopyrite, as well as minor tetrahedrite/tennantite. The two syn-compressional (syn-Variscan) vein samples are unmineralized/barren. All fluid inclusions within the quartz veins show a major liquid (L) phase and a minor vapour (V) phase with various volumes. The quartz veins show many secondary and pseudosecondary fluid inclusions along healed fractures. For the pre-Variscan veins, fluid inclusion data suggest multiple fluid pulses with moderate to high salinities and homogenisation temperatures of up to 314 °C (Fig. 2a). For the syn-Variscan veins the homogenisation temperature is around 200 °C with moderate salinities (Fig 2b).

Re-Os MOLYBDENITE GEOCHRONOLOGY

A fine grained (grain size < 2 mm) molybdenite sample from Mountain Mine spoil possesses 43.9 ± 0.2 ppm Re, 27.6 ± 0.1 ppm ^{187}Re and 169.1 ± 0.8 ppb ^{187}Os. The ^{187}Re-^{187}Os data yield to a model age of 366.4 ± 1.9 Ma for the molybdenite mineralization. A molybdenite sample from Caminches Mine spoil is also fine grained and has 3.83 ± 0.04 ppm Re, 2.41 ± 0.03 ppm ^{187}Re and 14.78 ± 0.16 ppb ^{187}Os. The ^{187}Re-^{187}Os model age is 367.3 ± 5.5 Ma.

CONCLUSIONS

The Allihies Mining District is dominated by two kinematically distinct quartz veining generations:

(1) Quartz veins with a general E-W strike are associated with early-extensional faults. These veins bear the primary copper mineralization as mainly chalcopyrite, bornite, tetrahedrite/tennantite and molybdenite. The timing of the mineralization is dated by molybdenite Re-Os geochronology of 367.3 ± 5.5 to 366.4 ± 1.9 Ma. The dates coincide with basin development and shortly post-date the early sedimentation sequences during the Upper Devonian (Fig. 3a).

(2) Syn-Variscan veins occur as saddle reefs and *en echelon* tension gash shear structures. Sub-horizontal veins crosscut early extensional structures (Fig. 3b).

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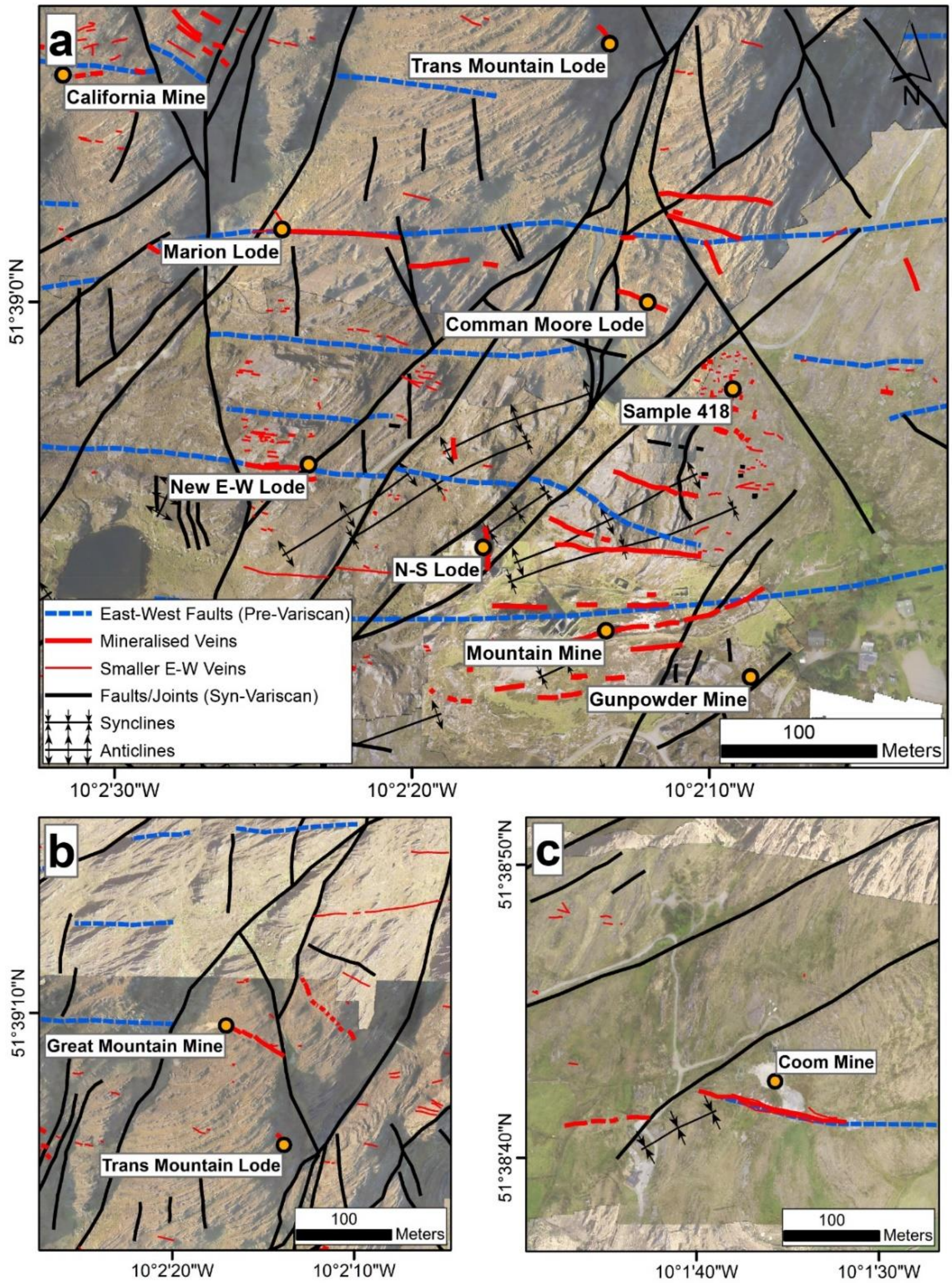


Fig. 1. *Map with syn-Variscan structures affecting the pre-Variscan faults and veins* ***a****) major lodes of the Mountain Mine Area with pre- and syn-deformation structures.* ***b****) sinistral faulted lode of Great Mountain Mine* ***c****) sinistral faulting of Coom Lode (ESE of Mountain Mine).*

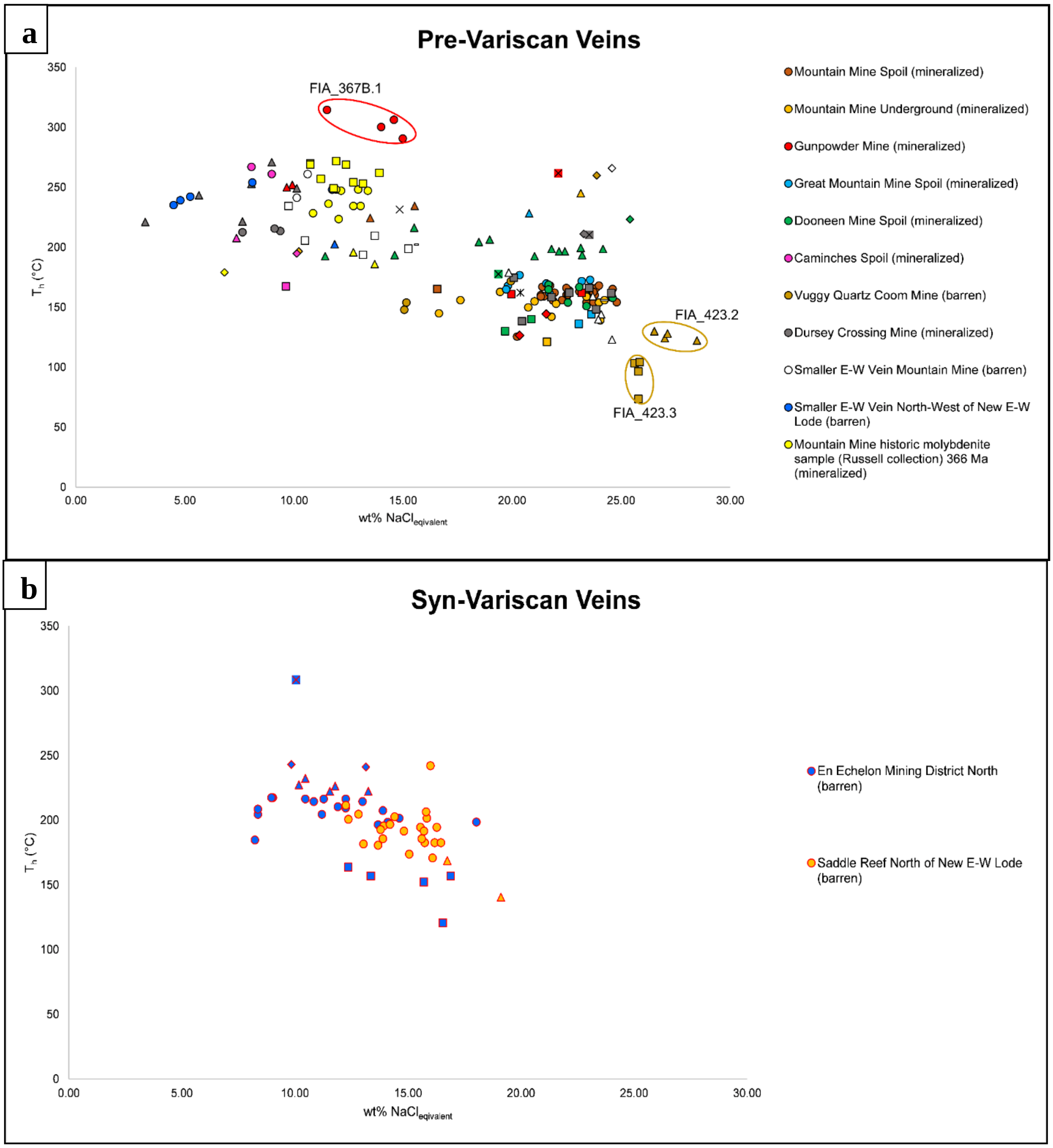


Fig. 2. *Fluid inclusions from samples of the Allihies Plot of the salinity wt% NaCl$_{equiv}$ versus the homogenisation temperatures T_h (°C). The different colours show the various locations, and the symbols indicate the individual fluid inclusion assemblages (FIA) within one sample.* ***a****) Early extensional (Pre-Variscan) vein samples.* ***b****) Compressional (Syn-Variscan) vein samples.*

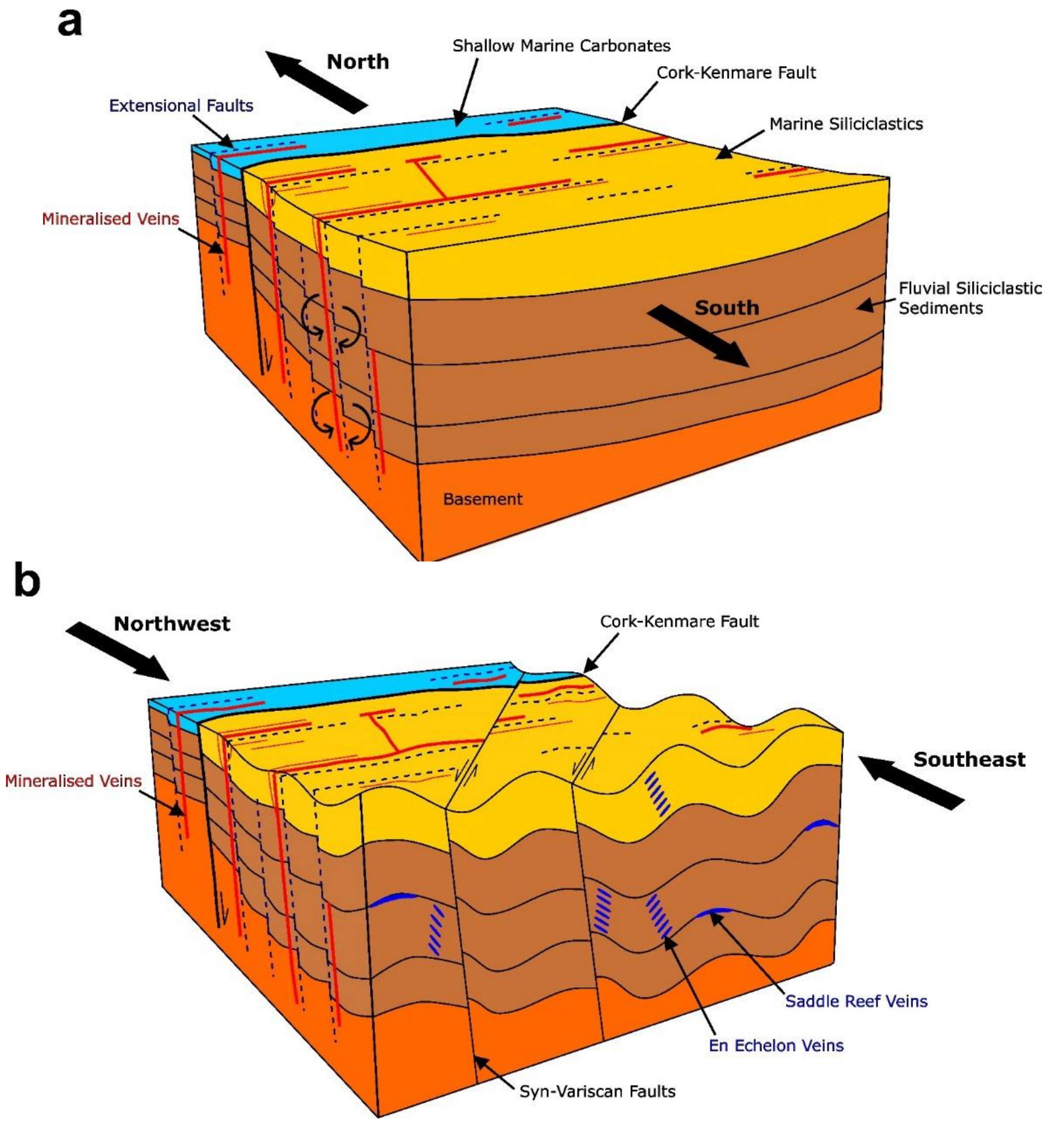


Fig. 3. *Schematic model of the vein development, mineralization and structural evolution of the Munster Basin and South Munster Basin (not to scale).* ***a****) North-South extension listric subsidence and alluvial sedimentation into the Munster and South Munster Basin. Active Extensional Faults, parallel aligned to the Cork-Kenmare Fault, provide fluid pathways for the precipitation of mineralized quartz veins.* ***b****) Syn-Variscan compression causes cleavage, folding and faulting of the basin sediments. Cleavage development within early extensional quartz veins and sinistral faulting. Formation of syn-compressional saddle reef and en echelon veins.*

EARLY CAREER POSTERS

A NEW NATIONAL GROUNDWATER CHEMISTRY DATABASE: COLLATING AVAILABLE INFORMATION AND ACTIVELY ACCEPTING NEW DATA

Seán Wheeler

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

GROUNDWATER 3D

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann
175 years | bliain 1845-2020

A New National Groundwater Chemistry Database

Collating available information and actively accepting new data

Seán Wheeler[2], Katie Tedd[1], Shane Carey[1], Coran Kelly[2], Monica Lee[1], Melissa O'Keefe[1], Sara Raymond[1]

[1]Geological Survey Ireland [2]TOBIN Consulting Engineers

Current Data Sources

Geological Survey Suirbhéireacht Gheolaíochta Ireland | Éireann

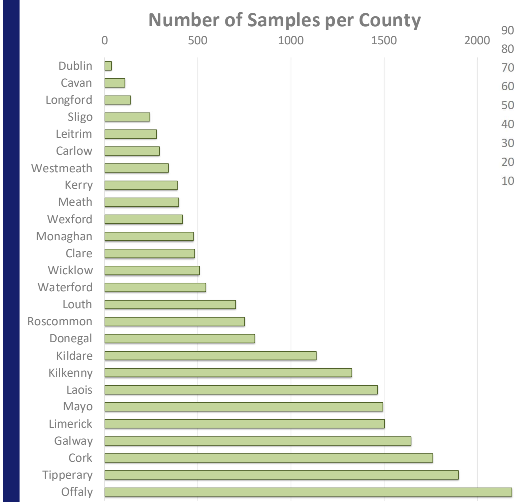
epa Environmental Protection Agency An Ghníomhaireacht um Chaomhnú Comhshaoil

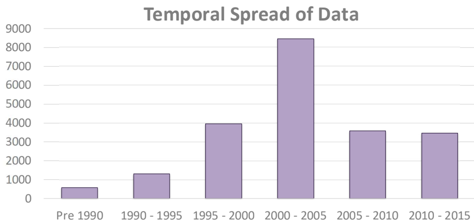
National Federation of Group Water Schemes

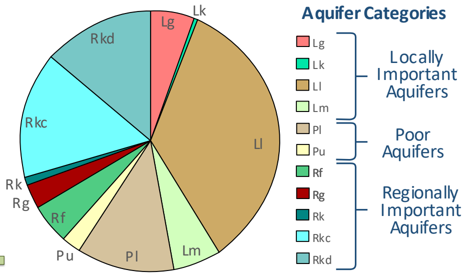
New Sources

Please Contact:
groundwaterinfo@gsi.ie

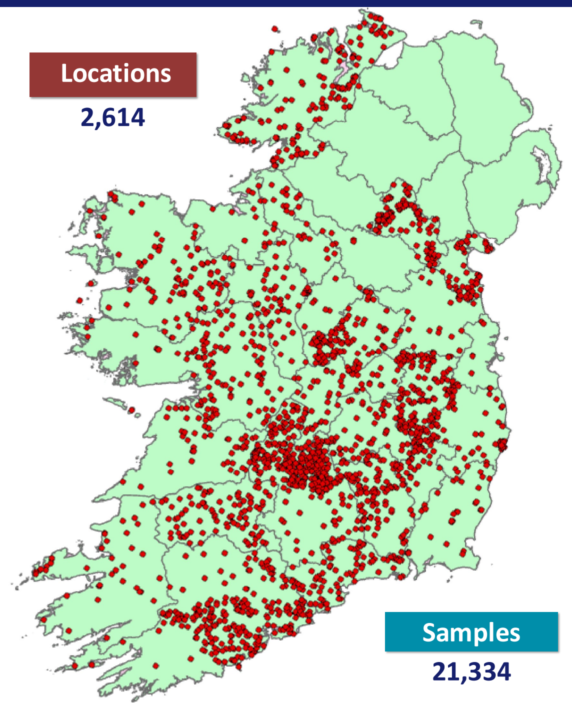
Summary Statistics







Spatial Distribution of Data



Composition of the Dataset

% Samples that have data for a given parameter

- 90 – 100 %
- 70 – 90 %
- 30 – 70 %
- 10 – 30 %
- 0 – 10 %

Borehole Details

- Sample ID
- Source
- Date
- Easting
- Northing
- County
- Catchment
- Aquifer Category
- Rock Unit
- Comments

Field Parameters

- pH
- Temperature
- ORP
- Colour
- Dissolved O2
- Electrical Conductivity
- Turbidity
- Biological Oxygen Demand

- Total Dissolved Solids
- Total Suspended Solids

Nutrients

- Nitrite
- Nitrate
- Ammonium
- Phosphate
- Non-Purgeable Organic Carbon
- Total Organic Carbon
- Total Inorganic Carbon
- Total Nitrogen
- Molybdate Reactive Phosphorus
- Total Phosphorus

Major/Minor Ions

- Total Hardness
- Alkalinity
- Calcium
- Sodium
- Potassium
- Magnesium
- Chlorine
- Sulphate
- Fluoride
- Iron
- Manganese
- Barium
- Strontium

Trace Ions

- Silver
- Aluminum
- Arsenic
- Boron
- Beryllium
- Cadmium
- Cobalt
- Chromium
- Copper
- Mercury
- Molybdenum
- Nickel
- Lead
- Antimony
- Silica
- Uranium
- Zinc

Microbial

- Coliforms
- E-coli
- Faecal Coliforms
- Faecal Streptococci

Calculated Fields

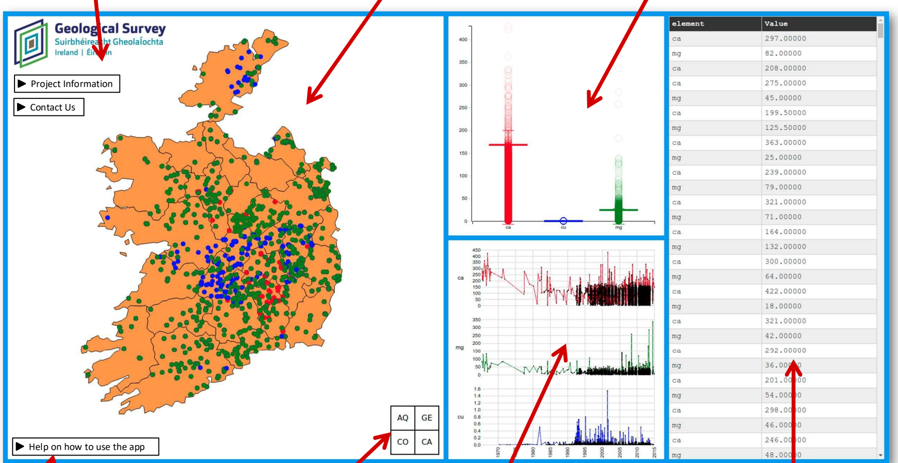
- Hardness Category
- Bicarbonate
- Ionic Balance

Web-Application

Project and Contact Info
Information about the Groundwater 3D project and contact info for contributing or requesting data.

Spatial Display
- Coloured by parameters chosen (up to 3 together)
- Zoom in to approximately county scale

Box-Whisker Plots
Plots give an indication of the concentration distribution over the chosen points and parameters



Help
Some info on how to use the app (e.g. create polygons to investigate data in a user defined area

Filter By:
- Aquifer
- County
- Geology
- Catchment

Time-Series Graphs
Time series comparison of selected data

Data Table
Data table for each of the three selected parameters showing the parameter, value, sample date and location ID (will be the same for samples from the same borehole)

Data Availability
The full dataset will be available to download from the GSI website soon. However, it will not be possible to directly extract data from the above web application.

Data Limitations and Assumptions
The list of parameters given here is not exhaustive and the GSI continue to add to both the number of samples and the number of parameters, particularly as more data sources become available. Additional assumptions have been made in preparing the dataset and conversions have been made where appropriate to simplify the number of parameters (e.g. Nitrate as N converted to Nitrate as NH3). A full explanation of all of these assumptions and alterations will be available within the metadata associated with the dataset.

GROUNDWATER: A POTENTIAL PATHWAY FOR THE SPREAD OF ANTIMICROBIAL RESISTANCE?

Luisa Andrade

GROUNDWATER: A POTENTIAL PATHWAY FOR THE SPREAD OF ANTIMICROBIAL RESISTANCE?

Luisa Andrade[1,2,3], Carlos Chique[1,2,3], Paul Hynds[3,4], John Weatherill[1,2,3], Jean O'Dwyer[1,2,3]

[1] School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland; [2] Water and Environment Research Group, Environmental Research Institute, Cork, Ireland; [3] Irish Centre for Research in Applied Geoscience, University College Dublin, Dublin, Ireland; [4] Environmental Sustainability and Health Institute, Technological University Dublin, Dublin, Ireland

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

iCRAG IRISH CENTRE FOR RESEARCH IN APPLIED GEOSCIENCES

Geological Survey Suirbhéireacht Gheolaíochta Ireland | Éireann

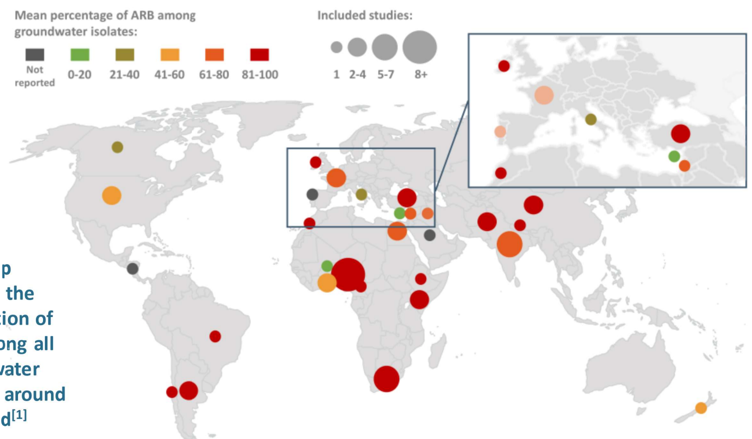


Fig.1 Map showing the distribution of ARB among all groundwater bacteria around the world[1]

BACKGROUND

- Antimicrobial resistant bacteria (ARB) represents a significant public health threat
- The role of natural environments, including groundwater systems, has been increasingly recognised in its spread
- The first global systematic review on this topic (developed as part of this research [1]) found that, where present, on average 80% of global groundwater bacteria were resistant to at least 1 antimicrobial (Fig.1)
- The current study is the first country-wide research which seeks to quantify (and identify drivers for) the presence of ARB In groundwater environments in the RoI

METHODS

- 132 private wells from 21/26 counties in the RoI were included in the current study (Fig. 2)
- Drinking wells were sampled in autumn 2019 and summer 2021
- Samples were tested for *Escherichia coli* and, where present, their antimicrobial susceptibility was tested using the disc diffusion method

RESULTS

- In total, 42 wells (32%) harboured *E. coli* at least once (Fig.2), with 35 contaminated samples in autumn 2019 and 19 in summer 2021
- 97% of groundwater-derived *E. coli* (n=49/51) were resistant to at least one antimicrobial, the most common being Streptomycin
- Rates of resistance in *E. coli* were similar across both sampling times, being marginally higher in summer 2021
- Results align with a previous study[2] done in the mid-west, where all groundwater *E. coli* were resistant to at least one antimicrobial

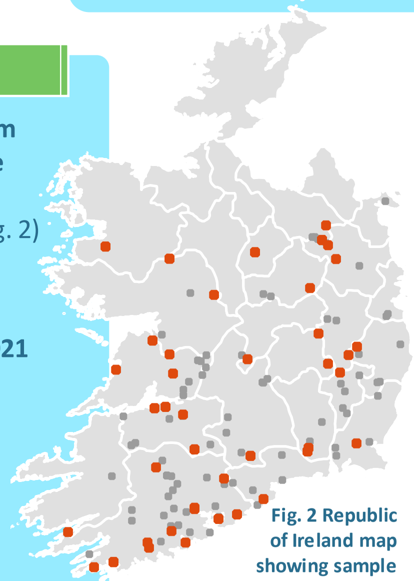


Fig. 2 Republic of Ireland map showing sample locations (■) and locations where *E. coli* were found (■)

WORK GOING FOWARD

- Identify the environmental and anthropogenic drivers of ARB in Irish groundwater systems
- Quantify the influence of metal contamination in the resistance displayed by *E. coli* within groundwater systems in the RoI

TAKE AWAYS

- GROUNDWATER IS A POTENTIAL PATHWAY FOR THE SPREAD OF ANTIMICROBIAL RESISTANCE GLOBALLY AND IN IRELAND
- Results from the complete study will provide insights into the environmental, hydrogeological and/or anthropogenic drivers of antimicrobial resistance in Irish groundwater supplies

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[2] O'Dwyer J, Hynds P, Pot M, Adley CC, Ryan MP. Evaluation of levels of antibiotic resistance in groundwater-derived E. coli isolates in the Midwest of Ireland and elucidation of potential predictors of resistance. *Hydrogeology journal*. 2017.

FUNDERS:

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sfi
European Union European Regional Development Fund

3D MODELLING THE STRUCTURE AND HYDROGEOLOGY OF THE CASTLECOMER PLATEAU

Simon Vokes

3D modelling the structure and hydrogeology of the Castlecomer Plateau

Simon Vokes[1], Koen Torremans[2], Katie Tedd[1] & Rob Doyle[2]
[1]Geological Survey Ireland, [2] University College Dublin

1. Abstract

This joint project between Geological Survey Ireland (GSI) and University College Dublin aims to integrate a myriad of data sets captured across the plateau to model both the geology and hydrogeology of the study area. Combining surface geology mapped by GSI with stratigraphic information captured during exploratory drilling by local collieries and group water schemes for local abstraction, we hope to create a conceptual 3D model of the subsurface to greater inform our understanding of the complexities of groundwater flow and local aquifer properties.

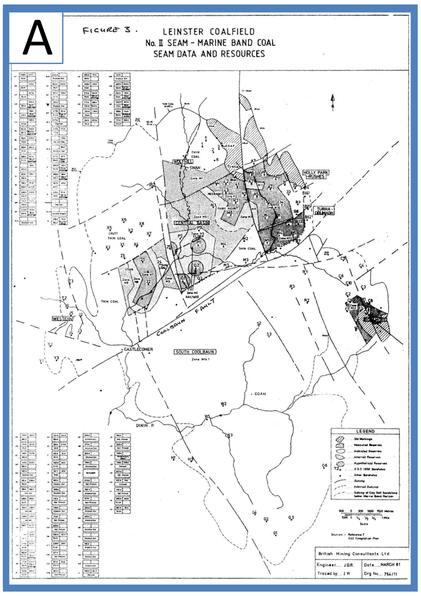


Figure A: Map of boreholes drilled by Castlecomer collieries showing old coal working areas.

Figure B: Sections of drill core from borehole GSI-85-3 held by Geological Survey Ireland taken from the Castlecomer plateau.

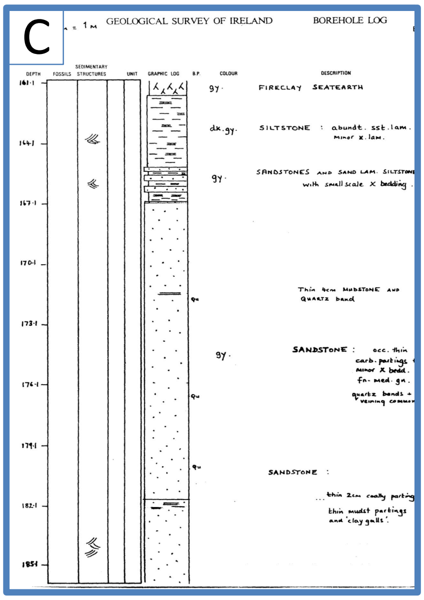


Figure C: A sample of the log of GSI-85-3 (Higgs & O'Connor 2005).

2. Data & Methods

This was the first known attempt to enter many of the paper logs captured across the region during exploratory drilling by local collieries into a digital 3D geological model.

Logs were analysed for units that could provide good stratigraphic control on modelled units such as the many named coal beds, fossil horizons and easily identified lithologies such as the Clay Gall and Swan Sandstones. Coordinates for these wells were then obtained from georeferenced workings maps (Fig.A) in ARCGIS.

Core from the plateau (Fig.B) held by GSI was examined in combination with existing logs (Fig. C) to aid future analysis of the lithologies for input into the model.

The stratigraphic information captured in these logs was then entered into Leapfrog and given surface constraints by feeding the model mapped surface geology information captured by GSI.

Pumping test information generated by drilling for group water schemes across Castlecomer were then added to the project for later analysis.

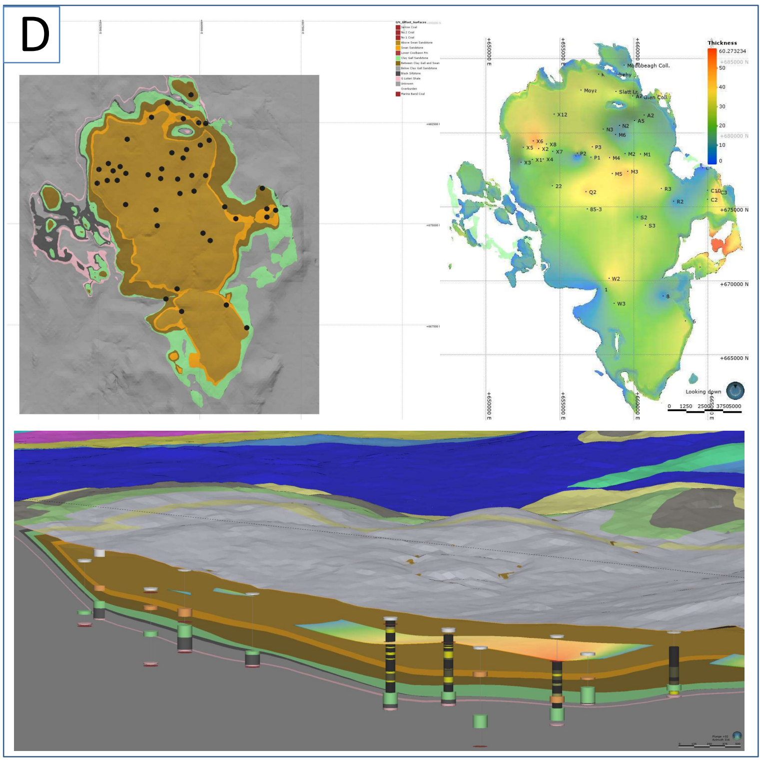


Figure D: Overview model of the Castlecomer plateau with thickness map of Clay Gall Sandstone Aquifer.

3. Results

By digitising many of the boreholes captured across the Castlecomer Plateau and the stratigraphic information therein, and combining it with the mapped geology captured by Geological Survey Ireland, we have been able to create a constrained 3D model of the local subsurface.

This has been a great help in visualising the confined Swan and Clay Gall Sandstone aquifers that are hosted in the succession. Characteristics such as aquifer thicknesses and relationships with the many faults can be observed with greater clarity in three dimensions and will serve as a starting point for further work on the plateau.

4. Further Work

Future work will comprise:

- Examination of group water scheme pump testing rates and their relationship to the structural geology of the plateau;
- Refinement of surface geology constraints with outcrop information from mapping;
- Addition and refinement of borehole log interpretation in the model;
- Addition of medium to small scale faults across the modelled area.

Further Reading:

- Higgs & O'Connor (2005). Stratigraphy and Palynology of the Westphalian Strata of the Leinster Coalfield, Ireland. Irish Journal of Earth Sciences.
- Daly et al. (1980). Fault control of groundwater flow and hydrochemistry in the aquifer system of the Castlecomer Plateau, Ireland/Quarterly Journal of Engineering Geology and Hydrogeology.

CONCEPTUAL MODELS OF THE GEOLOGICAL CONTROLS ON THE FATE AND TRANSPORT OF NITRATE AND PHOSPHORUS IN GROUNDWATER FOR THE UPPER BANN CATCHMENT, NORTHERN IRELAND

Hamish Johnson

Conceptual models of the geological controls on the fate and transport of nitrate and phosphorus in groundwater for the Upper Bann catchment, Northern Ireland

Hamish Johnson[1], Jean-Christophe Comte[1], Ulrich Ofterdinger[2], Rachel Cassidy[3], Mads Troldborg[4]

[1] School of Geosciences, University of Aberdeen; [2] School of Natural and Built Environment, Queen's University Belfast; [3] Agri-Food and Biosciences Institute; [4] Information and Computational Sciences Group, James Hutton Institute.

Introduction

Groundwater provides an important nutrient transport pathway in agricultural river catchments delivering Nitrate (N) and Phosphorus (P) to human and ecological receptors. This project aims to improve our understanding of the hydrogeological controls on groundwater nutrient fate and transport to improve the management of diffuse nutrient pollution. The preliminary conceptual models presented here have been developed from a literature review of hydrogeological controls on groundwater nutrient transport and a desk study of the Upper Bann field site.

Geochemical controls

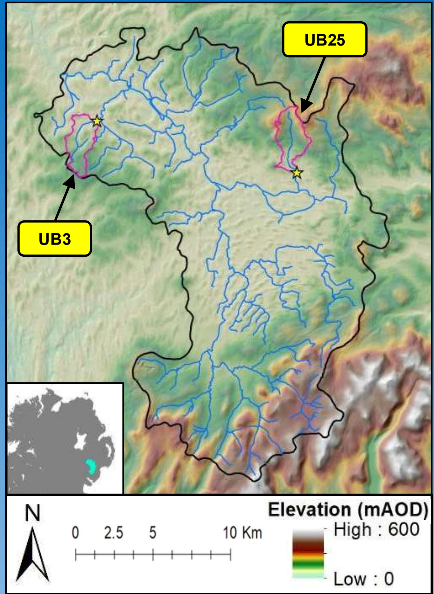
Phosphorus (P): Poor mobility in groundwater due to reversible adsorption to clays and metal (oxyhydr)oxides, and potential for long term storage through mineral precipitation. Higher risk of groundwater P transport associated with: (1) low pH; (2) reducing conditions; and (3) saturation of P sorption sites.

Nitrate (N): Highly mobile in groundwater but can be fully degraded through denitrification reactions requiring: (1) low dissolved oxygen; (2) source of electron donors (e.g., organic carbon, Fe^{2+} etc); and (3) sufficient time for reactions to proceed.

Hydrogeological controls

The hydrogeological setting of river catchments will dictate the distribution of groundwater flow pathways and therefore how nutrients are transported through the subsurface, and the different geochemical environments nutrients encounter. The key hydrogeological factors influencing groundwater nutrient transport include:

- Groundwater flow type: intergranular vs fracture.
- Depth to groundwater table.
- Position of groundwater system i.e., recharge vs discharge area.
- Flow pathway length and residence time.
- Connection and compartmentalisation between different aquifers.

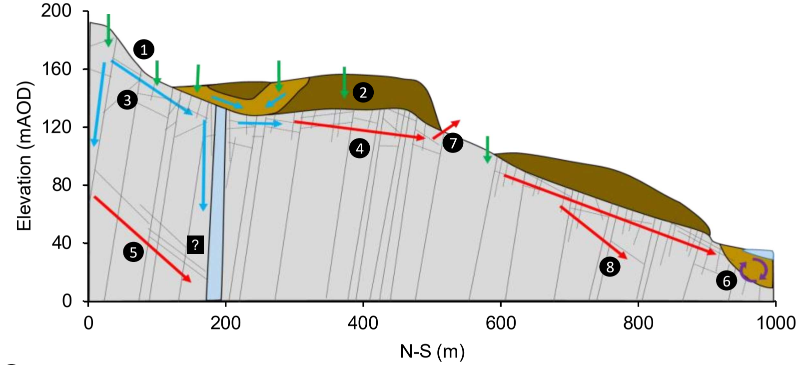


Field site: Upper Bann, Co. Down

- Lowland drumlinised landscape dominated by grassland agriculture.
- High groundwater P and high baseflow P.
- N impacts vary between sub-catchments.
- In this project, two contrasting headwater sub-catchments will be investigated for hydrogeological controls on groundwater nutrient transport.

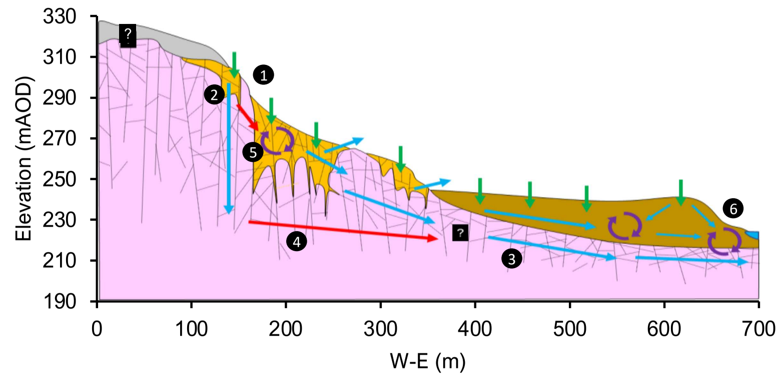
University of Aberdeen; Queen's University Belfast; UKRI Natural Environment Research Council; afbi Agri-Food & Biosciences Institute; The James Hutton Institute

UB3 Drumlinised metasedimentary bedrock aquifer



1. Oxic GW recharge through discontinuities in glacial overburden
2. Anoxic GW recharge through thick glacial till.
3. Low denitrification in unconfined shallow fractured bedrock.
4. High denitrification where fractured bedrock is confined by glacial till.
5. High denitrification in deep fractured bedrock.
6. Limited hyporheic circulation in small swales.
7. Mobilisation of P stored in soils and the unsaturated zone by anoxic groundwater upwelling.
8. P immobilisation in deep alkaline groundwaters.

UB25 Granodiorite glacial meltwater valley



1. High groundwater recharge through weathered bedrock and sandy glacial till.
2. Redox conditions of saprolite will be highly dependent on clay mineralogy.
3. Oxic conditions persist along shallow groundwater flow pathways in fractured bedrock aquifer.
4. Deeper groundwater flow pathways may be reducing due to interaction with aquifer minerals.
5. Groundwater mixing in zones of deep bedrock weathering.
6. Large hyporheic circulation due to high permeability, sandy glacial till.

Aquifers

Glacial deposits
- Clayey
- Sandy

Weathered bedrock
- Igneous rock

Fractured bedrock
- Basalt dyke intrusion
- Granodiorite
- Metasediment

Hydrological pathways

- Recharge
- Oxic GW flow
- Anoxic GW flow
- Mixing
- Unknown

Conclusions

- Redox conditions play a key role on N and P transport in groundwater.
- Granitic aquifers are expected to attenuate more agricultural P, but agricultural activities may contribute to P production from enhanced weathering.
- Granitic aquifers are expected to be more vulnerable to N pollution relative to argillaceous metasedimentary aquifers.

Further work

1. Ground-based geophysical surveys to characterise hydrostratigraphy and hydrogeological parameters.
2. Collect groundwater samples for nutrient and residence time indicator analysis.
3. Test conceptual models with numerical modeling.

ARSENIC CONTAMINATION OF FRACTURED BEDROCK AQUIFERS IN THE PALAEOZOIC UNITS OF SOUTH-EAST IRELAND

Alex Russell

Arsenic Contamination of Fractured Bedrock Aquifers in the Palaeozoic Units of South-East Ireland

Alex Russell[1,2,4], Frank McDermott[2,4], Tiernan Henry[3,4], Liam Morrison[3,4]
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Background

Long-term exposure to dissolved inorganic arsenic (As) through contaminated drinking water has been linked to numerous health risks including skin ailments and cancers. The World Health Organisation (WHO) has set a global recommended limit of 10 µg/L in drinking water for this reason. In Ireland, up to 200,000 unregulated private water supplies are in active use, but reliable metal/metalloid data at the µg/L remain scarce. Three areas were identified using existing geochemistry and Tellus datasets for focused work on As contamination of private wells across South-East Ireland, (Fig. 1).

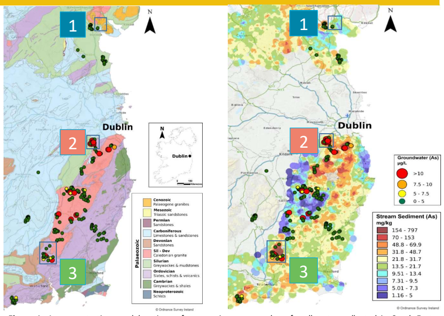
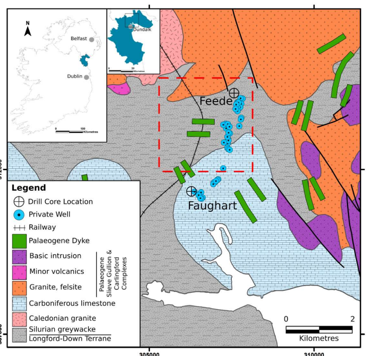


Figure 1. As-concentrations and locations of reconnaissance samples of well water collected in South-East Ireland, with (a) GSI 1:500K bedrock geology and (b) Tellus stream sediment As-anomalies base-maps.

Arsenic is odourless, tasteless, and colourless, and so can effectively remain 'invisible' in drinking water alongside other naturally-occurring or 'geogenic' contaminants such as chromium, and uranium. Identifying potential geogenic contamination is essential to best protect the health and wellbeing of well users.

1. Louth: Silurian Greywackes



An area of elevated As-concentrations in private wells (up to 60 µg/L) was identified along the contact between the Tertiary Slieve Gullion Complex and the Silurian Longford-Down Terrane (Fig. 2). The Geological Survey Ireland (GSI) drilled two cores (Feede & Faughart) to identify potential sources of arsenic (Fig. 3).

Figure 2. (Left) Geological map (GSI 1:500k) of an area of As-contamination in Co. Louth, also showing the locations of the 2 cores drilled by the GSI.

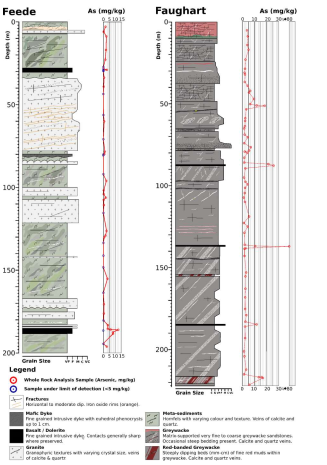


Figure 3. Logs of Feede and Faughart cores with total whole-rock arsenic (As) concentrations at given depth intervals.

Common to both cores are basaltic cone sheets, with whole-rock As-concentrations up to 80 mg/kg present at c. 136 m depth in the Faughart core, (Fig. 3). The average across this cone sheet set is 23 mg/kg which represents an enrichment of arsenic relative to global and regional averages of 2 – 5 mg/kg for basalts and dolerites (Fig. 4).

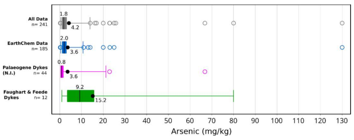


Figure 4. Tukey boxplot of dyke As-concentrations for this study area, other Irish Palaeogene dykes and online international databases. Circle outliers are in the top/bottom 5% or 95%, whiskers are the 5% and 95% values

SEM-EDX analysis was carried out on samples of As-enriched basalts. As-bearing sulphides (<20 µm) were identified as the only As-bearing phase within these basalts, (Fig. 5). Correlations are seen with Co and Ni, indicating a cobaltite-type mineralogy. Oxidation of these sulphides by groundwater percolation through fractures in the basaltic intrusives is the likely mobilisation mechanism for As-contamination in this area.

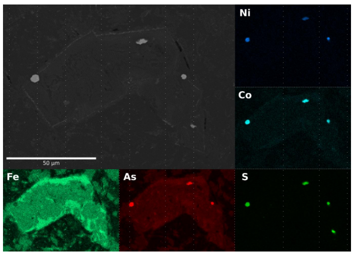
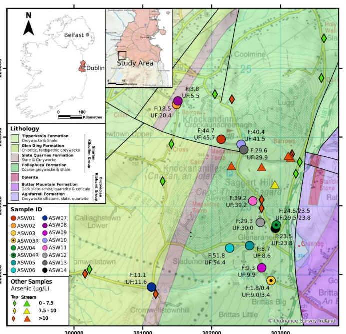


Figure 5. (Right) SEM BSE and EDX-mapping images showing As-Co-Ni bearing sulphides within a sample of basalt at 136m in the Faughart core.

2. Dublin: Silurian Greywackes



An As stream sediment anomaly was used to identify a region of elevated levels of arsenic in groundwater (up to c. 50 µg/L) (Fig. 6), after sampling 29 private wells. The bedrock geology is Silurian greywacke and slate units, forming a poorly-productive fractured bedrock aquifer. Detailed sampling was completed on 14 wells, directly from the well or nearest tap, using low-flow & clean-hand/dirty-hand sampling protocols. In-situ measurements of pH, ORP and conductivity were recorded (Fig. 7). A further 4 stream samples were found to be elevated in arsenic (up to 85 µg/L).

Figure 6. (Left) Geological map (GSI 1:100k) showing detailed sampling locations with As-concentrations for filtered (F) and unfiltered (UF) samples, in addition to As-concentrations for reconnaissance samples of taps and streams.

Arsenic is present primarily in dissolved form, exhibiting a range of correlations with physiochemical parameters (Fig. 7a-e). Positive correlations are noted with ORP (up to 350 mV), and negative with pH, suggesting sulphide oxidation as a mobilisation mechanism. Notably 3-4 samples outlie trends (blue) which may represent separate flow systems at greater depths. Sulphate (SO_4), however, shows a negative trend with increasing As-concentration, (Fig. 7f). Iron and manganese do not show significant correlation (Fig. 7g-h), indicating potential Eh-pH effects within the water systems.

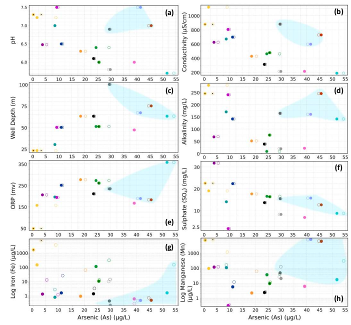
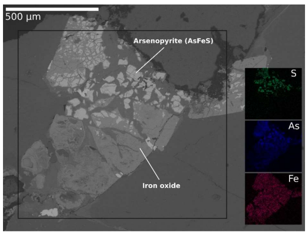


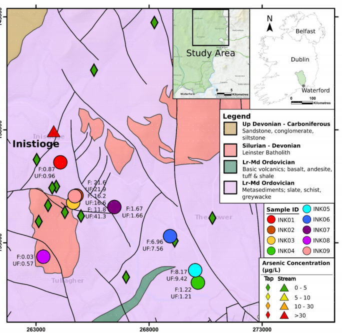
Figure 7 (a-h). (Right) A variety of physical/geochemical parameters vs As-concentration. Blue shaded areas highlight potential outliers with depth relations. Open symbols represent unfiltered samples, closed represent 0.45 µm filtered samples .



SEM-EDX analysis and mapping has identified weathered As-bearing sulphides (Fig. 8), associated with iron (Fe), giving an arsenopyrite mineralogy (FeAsS). Sulphide oxidation is the likely As-mobilisation mechanism, although iron-oxides may also act as a secondary source/sink. There is evidence of arsenopyrite weathering to form iron oxides (Fig 8).

Figure 8. (Left) SEM BSE and EDX-mapping image of a weathered arsenopyrite crystal within Silurian greywacke in Co. Dublin.

3. Kilkenny: Ordovician Meta-sediments



A further area identified from anomalous As-concentrations in stream sediments was shown to contain significantly elevated groundwater As, with concentrations up to 60 µg/L. A total of 21 private wells were sampled within a poorly productive fractured bedrock aquifer comprised of Ordovician meta-sediments and Caledonian granites, (Fig. 9). Detailed sampling was completed on 9 wells, directly from the well or nearest tap, using low-flow & clean-hand/dirty-hand sampling protocols. In-situ measurements of pH, ORP and conductivity were recorded (Fig. 10).

Figure 9. (Left) Geological map (GSI 1:500k) showing detailed sampling locations with As-concentrations for filtered (F) and unfiltered (UF) samples, in addition to As-concentrations for reconnaissance samples of taps and streams.

Arsenic is primarily dissolved, as shown by similar concentrations in filtered/unfiltered samples (0.45 µm) (Fig. 10). The samples exhibit a range of correlations between As and physiochemical parameters (Fig. 10a-d). Higher ORP (>100 mV), conductivity (<200 µS/cm), alkalinity (<100 mg/L) are all associated with higher As-concentrations. Waters at pH <6.5 are low in arsenic, with possible $Fe(OH)_3$ adsorption effects in the aquifer systems at this pH range. Sulphate (SO_4) does not trend with arsenic (Fig. 10e), however, sample INK06 (blue) outlies for both sulphate and cobalt (Co) (Fig. 10f). A surface water sample collected flowing from an outcrop of quartz veins in Ordovician meta-sediments in the area yielded 134 µg/L As, (Fig. 11a).

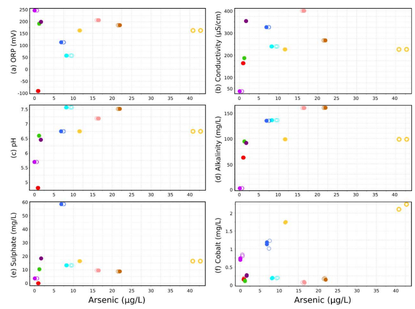


Figure 10 (a-h). A variety of physical/geochemical parameters vs As-concentration. Open symbols represent unfiltered samples, closed represent 0.45 µm filtered samples .

SEM-EDX analysis has shown that several As-bearing phases exist, associated with both these quartz veins and disseminated within the Ordovician meta-sediments, (Fig. 11). These range in composition from arsenopyrite (Fig. 11b) to Co-As bearing phases (Fig. 11c), which may explain possible trends with cobalt within groundwater samples. Oxidative weathering of these sulphides likely represents the primary sources of arsenic within this area.

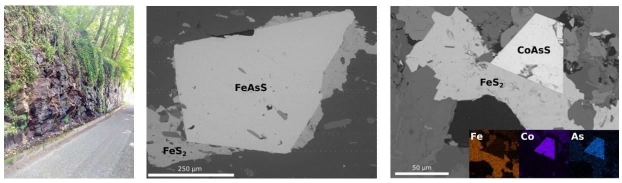


Figure 11. **(a)** Outcrop image showing quartz veins (arrows) with arsenopyrite mineralisation along contacts, spaced at approx. 1 m distance **(b)** SEM BSE of a arsenopyrite (FeAsS) phase with pyrite (FeS_2) overgrowth. **(c)** SEM BSE and map of a disseminated Co-As sulphide phase with pyrite (FeS_2) overgrowth.

Conclusions

1. Regional geochemical mapping of the surface environment including stream waters, soils, and sediments are useful tools in the identification of geogenic As groundwater contamination.

2. Localised sulphide oxidation represents the primary mobilisation process across all three study areas in the Palaeozoic units in SE Ireland, with an association to cobalt in two of the areas.

3. A health risk exists for rural populations where water quality testing for geogenic contaminants has not been carried out, especially given the existence of similar geological environments elsewhere e.g. Dalradian meta-sediments in NW Ireland.

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David Ball & Associates

SESSION II

THE ROLE OF GROUNDWATER IN THE WORLD WATER QUALITY ALLIANCE

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ABSTRACT

United Nations Environment Assembly (UNEA) Resolution 3/10 on "Addressing water pollution to protect and restore water-related ecosystems" (UNEP/EA.3/Res.10) requested UN Environment (UNEP) to develop a global water quality assessment in collaboration with UN-Water and relevant stakeholders. During the Inception Meeting for the Assessment, carried out in the second half of 2018, around 50 organizations (UN, research, civil society, private sector) decided to form a World Water Quality Alliance (WWQA) as an open community of practice which advocates the central role of freshwater quality in achieving prosperity and sustainability.

The role of groundwater within the Alliance is presented here, especially the past work and future plans of the Friends of Groundwater (FoG), a group of about 30 members representing 20 institutions and organizations, which is one of the workstreams under the alliance.

Key words: *Groundwater quality, global assessment, upscaling, groundwater portal.*

THE ROLE OF GROUNDWATER IN THE WORLD WATER QUALITY ALLIANCE

The World Water Quality Alliance (WWQA) is a voluntary and flexible global multi-stakeholders network that advocates the central role of freshwater quality in achieving prosperity and sustainability. The WWQA explores and communicates water quality risks in global, regional, national and local contexts, pointing towards solutions for maintaining and restoring ecosystem and human health and well-being. Moreover, it provides a participatory platform for water quality assessments addressing priority topics relevant to water governance, scalable water solutions and emerging issues in water management.

The Alliance focuses on deliverables on three levels:

1. A global assessment of freshwater quality drawing on science – technology – innovation, including a data fusion approach combining in-situ monitoring, modelling and remote sensing.

2. Horizon scanning, agenda setting and investigating selected priority topics based on a collective prioritization process to identify persistent or emerging water quality issues of key environmental and socio-economic concern.

3. Following a bottom up-approach, co-designing and operationalization of water quality related services and products, based on a moderated in-country stakeholder driven bottom-up process to identify local demands and needs.

The World Water Quality Alliance (WWQA) is supported by the work carried out by various workstreams. These are:

- Baseline World Water Quality Assessment
- GlobeWQ STI Platform development
- Capacity Development Consortium (CDCm)
- Ecosystem
- Friends of Groundwater (FoG)
- Plastics
- Social Engagement Platform
- Citizen Science - Citizen Data for SDG Indicator 6.3.2 - One way to fill the Data Void
- Scenarios - Global Scenarios Ecosystem Health
- Scenario Analysis for World Water Quality Assessment
- Towards a Pan-African Water Quality Program (PAWaQ)
- WaterForCE
- Youth Action for World Water Quality

Groundwater plays a role at different degrees in most of the mentioned workstreams, but in one of them plays a central role: the Friends of Groundwater (FoG), which was created to support the global assessment of groundwater quality.

THE FRIENDS OF GROUNDWATER (FOG) WORKSTREAM

The Friends of Groundwater (FoG) is a group of about 30 members representing 20 institutions and organizations set up to improve the global knowledge base on groundwater quality. Its first activity, which was carried out throughout 2020, was the preparation of a comprehensive paper on the qualitative state of groundwater resources globally: “Assessing Groundwater Quality: A Global Perspective. Importance, Methods and Potential Data Sources”. The paper was presented at the 2nd annual global meeting of the World Water Quality Alliance 27-28 January 2021.This perspective paper aimed at giving a compelling argument for the importance of groundwater quality for human development and ecosystem health. It addressed the relevance of a global assessment, information to be assessed, related methods, data and information sources.

The assessment of global groundwater quality is a complex task, even more than the same endeavour for surface water, due to its hidden nature, three-dimensional distribution and long residence times, among others. In addition, knowledge and information necessary to produce a global groundwater quality assessment are highly dispersed. Finding answers to important questions such as “which contaminants are the most important and where are they found? Which places in the world need more attention and/or resources? Which organizations deal with groundwater quality and where?” is a lengthy and complex process.

The planning of urgently required activities to position groundwater central in the discourse towards achievement of the 2030 Agenda for Sustainable Development depends on awareness and a global sense of urgency supported by expert engagement. The FoG specialists convene as a high standard community of practice and has raised awareness of the importance of regional and global groundwater quality assessment to serve human and ecosystem health.

To tackle these issues, the FoG has started to collect and process relevant data and information to be made available in a structured way through a Global Groundwater Quality (GGWQ) portal. The portal aims to be the focal point for global groundwater quality information and activities, to improve the global knowledge base on groundwater quality, and to link to all (FoG members and others) portals and activities relevant to groundwater quality assessment at the regional/global scale.

DESCRIPTION OF THE GLOBAL GROUNDWATER QUALITY (GGWQ) PORTAL AND FUTURE FOG'S ACTIVITIES

The GGWQ portal (Figure 1) will promote a global assessment of groundwater quality highlighting its importance, methods and potential data sources. Relevant data and information collected and processed will therefore be accessible through the portal in a structured way, and updated regularly. This includes content on the global assessment, contaminants, activities, references, and more.

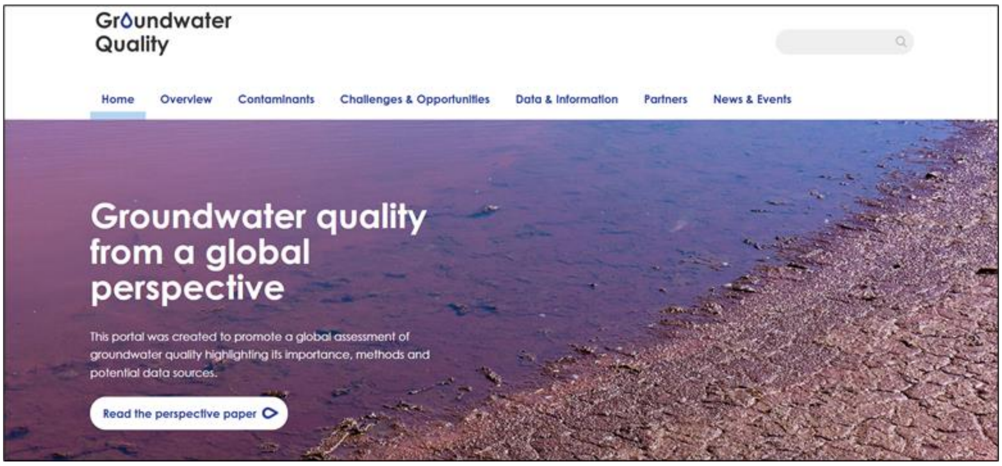

Figure 1: *Landing page of the Global Groundwater Quality Portal (https://groundwater-quality.org/).*

The GGWQ portal includes technical (ICT) tools: a reference database (Figure 2) and a graphical interface/map viewer (Figure 3), appropriate for spatial/geographic data such as overview maps. The reference database will collect the most relevant sources of literature and datasets on assessing groundwater quality in a global and regional scale. The map viewer is envisaged as a meta-portal or entry point to portals from different organisations, rather than a mega-database for storing/duplicating data already available elsewhere. The outcomes of FoG activities, via the groundwater quality portal, will feed other relevant portal/databases, especially the UNEP World Environment Situation Room (WESR).

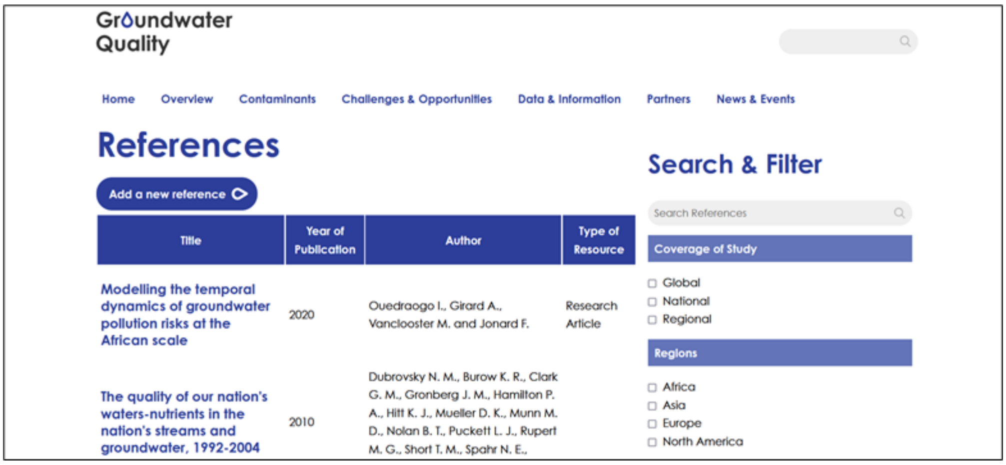

Figure 2: *References section under Data & Information (https://groundwater-quality.org/references).*

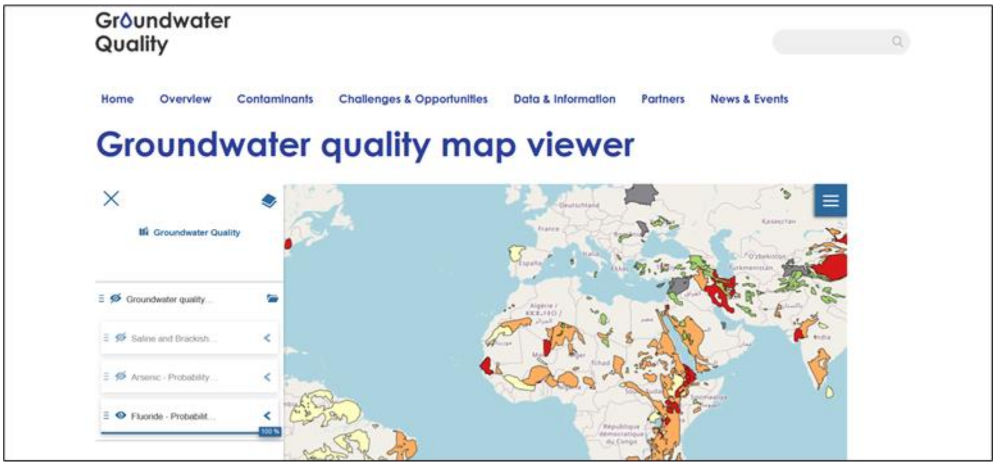

Figure 3: *Groundwater quality map viewer under Data & Information (https://groundwater-quality.org/groundwater-quality-map-viewer).*

The most important activities of the FoG are building a global Groundwater Quality (GQ) Assessment network, and upscaling, namely regionalisation of local assessments. The GGWQ portal will support the development of a global groundwater quality assessment based on upscaling and regionalisation of local assessments, including regional/global modelling, inclusion of use cases into regional assessment, remote sensing, Citizen Science, etc. In the long-term, the portal will be a knowledge base for further assessments of groundwater quality on regional basis worldwide. It will also serve as a focal info point for scientists, policymakers and general public and various other stakeholders.

The GQ Assessment network will be progressively developed through contributions of the specialists and institutions involved. The network will grow further, alongside development of future planed FoG activities. Some envisioned contributions are to provide assistance to national groundwater assessment programmes, advocacy at various levels, acquisition, preparation and execution of projects, raising awareness, promotion of innovative approaches and technologies, and similar. This will build on the existing work of GEMS/Water in connection with SDG target 6.3.2., and will be supported by the GGWQ portal.

In summary, the FoG aims to further develop as a focal point for regional/global groundwater quality assessment within WWQA, provide advice, guidance and scientific leadership. The GGWQ portal will assist in this task and be further developed accordingly, considering countries feedback, priorities of potential donors, and fellow specialists in related fields and the public.

REVEALING THE INVISIBLE: GEOLOGICAL SURVEY IRELAND'S NATIONAL KARST DATABASE

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ABSTRACT

Limestones underlie 40% of Ireland and much of this rock is karstified, with approximately 25% of the country underlain by highly karstified bedrock. Karst groundwater systems provide a significant proportion of Ireland's groundwater resources. Optimal management of these resources requires a deep understanding of karst systems and their relationships to the land, surface water and related ecosystems. The complexity of karst means that underground pathways can be unpredictable, and groundwater can move rapidly over long distances. This complexity presents challenges for the characterisation and visualisation of karst systems. The unpredictability of karst terrain also presents geotechnical engineering challenges; for example, 75% of the total length of motorway in Ireland is underlain by limestone. Irish karst landscapes contain solution features such as dolines and depressions, swallow holes, caves, sinking streams, turloughs and dry valleys. Although karst systems are difficult to 'see' underground, they nevertheless feature in the imagination of the general public as many of our best known geoheritage features are karst features (e.g., the Burren, the Aran islands, the Cuilcagh Lakelands Geopark, Dunmore Cave, etc.), and the karst landscape itself supports our tourism sector.

Geological Survey Ireland has sought to improve its understanding of the hydrogeology and geomorphology of Irish karst since the inception of the National Karst Database over 20 years ago. This paper outlines the evolution of the National Karst Database from 1996 including some recent improvements and additions to the datasets and viewers. We explore the benefits of making these data openly accessible to the public, and why it is important that the karst database continues to grow to meet the needs of our stakeholders. Geological Survey Ireland are experts in field mapping and verification of karst features, and in recent years we have also incorporated new technologies such as remote sensing and machine learning into our toolbox. New additions to the database include a national-scale map of turlough flood extents, with accompanying hydrographs and statistics at monitored sites. Using examples from our recently completed work with the National Federation of Group Water Schemes, we demonstrate the importance of understanding karst hydrogeology and the impacts it can have on groundwater quality, human health, and the environment. We also present recently collected karst data from Lough Carra, Co. Mayo, and use this to demonstrate the vast number of unmapped karst features that must exist unseen in Ireland today.

Key words: *karst hydrogeology, database, field mapping, turloughs, groundwater protection, tracer testing, remote sensing*

KARST IN IRELAND

Carbonate limestones underlie approximately 40% of the island of Ireland, including most of the major cities and towns and the best agricultural land (Drew, 2008). By far the most widespread carbonate rock is Carboniferous-age limestone. Karst features have been recorded in almost all Irish counties. Karst limestones are consequently a very important aspect of Irish hydrogeology.

Though the extent to which the limestones of Ireland are karstified is somewhat uncertain, it is probable that all limestones have experienced solutional weathering (Drew, 2018). The lithology and structure of our varied limestones mean that a wide variety of karstic landscapes are found, and a remarkable diversity of limestone landforms are in evidence. Irish karst landscapes contain solution features such as dolines and depressions, swallow holes, caves, sinking streams, turloughs and dry valleys, and are important destinations for tourism and recreation. In some areas the karstification of bedrock does not always result in karst landforms at surface, particularly in areas where bedrock is overlain by thick subsoils.

Ireland has world-famous karst, and two of our UNESCO Global Geoparks are well-known karst landscapes: The Burren and Cliffs of Moher Global Geopark and Marble Arch Caves Global Geopark. Our karst landscapes are also extremely important geoheritage sites. A broad range of archaeological material and objects has been found in Ireland's caves, with the oldest flint tools and human bones dating from the Mesolithic (8,000-4,000 BC). Cave sediment and speleothems are an important source of information on past climates, and the sediments found in palaeokarstic depressions allow the reconstruction of Ireland's post-Carboniferous past.

IRISH KARST HYDROGEOLOGY

The majority of Ireland's regionally important aquifers occur in limestones, and the largest springs, as well as the largest yielding boreholes in Ireland occur on karstified limestone (Drew, 2018). Many highly karstic areas are characterised by little or no surface water and often karst aquifers are the only sources of water in these areas for drinking and agriculture.

Irish karst groundwater systems incorporate a wide range of karst aquifer types, from fracture flow through to wholly conduit-dominated flow. As most karst in Ireland is lowland, the aquifers are complex with a high degree of interaction between surface water and groundwater. Karst aquifers are important sources of base flow to rivers, lakes and associated ecosystems providing up to 100 % of flow to rivers in drought conditions.

The Irish western lowlands are often characterised by high water levels and severe flooding in winter. Since 2016 Geological Survey Ireland has been collecting water level information from a series of turloughs throughout Ireland. The data was initially collected as part of the GWFlood project which aimed to address the data gap regarding groundwater flooding in Ireland. Karst waters, often highly mineralised, give rise to rich and varied characteristic floral and faunal communities. These groundwater dependent terrestrial ecosystems, which include turloughs, are often important protected wetland habitats for plant, invertebrate and bird communities (Johnston, 2018), and many in Ireland are protected under the EU Habitats Directive (92/43/EEC) and are designated as Special Areas of Conservation (SACs).

THE PROBLEM(S) WITH KARST

Karst groundwater systems are complex and can be unpredictable. This is especially true of Irish lowland karst, which is often covered in a mantle of glacial deposits. By their very nature karst aquifers are extremely heterogeneous and anisotropic, the flow can be non-linear and not easily described by numerical models, and as a result they are often difficult to understand. There may be no obvious topographical or piezometric gradient, which can make zones of contribution (ZOCs) to springs and boreholes hard to delineate with any certainty. Flow paths can be very long and extend beyond expected surface water catchment boundaries. Groundwater velocities can also be very high. Common karst landforms such as swallow holes and dolines can effectively puncture the protective layer of overlying sediment, allowing potential contaminants, often from a large area, to easily enter the karst aquifer. This diminished protection, coupled with the long and fast flow pathways, means karst aquifers can be extremely vulnerable to pollution events. This complexity presents challenges for the characterisation and visualisation of karst systems.

Karst can also pose challenges to construction projects. Geotechnical engineers and hydrogeologists involved in the design of these projects must consider the structural challenges posed by the potential for collapse and subsidence, and the hydrogeological connectivity between karst features and any potential receptors or end-users of the karst groundwater. Any changes in the karst groundwater system through, e.g., dewatering, must be carefully managed to prevent subsidence, and any contamination arising from construction can result in detrimental effects on the human and other ecological communities who depend on these karst water supplies.

A deep understanding of the karst groundwater system is critical in these projects and, depending on the level of information available in any given area, a detailed karst landform mapping exercise is often a prerequisite. Tracer testing may also be required to establish hydraulic connectivity between different areas. A comprehensive description of methodologies to deal with the challenges of karst hydrogeology is presented in Drew (2018).

As karst and caves are often hidden features in a landscape, they can remain under-researched and poorly managed. Even with advances in remote sensing and earth observation technology, the identification and verification of karst landforms can still prove difficult. Karst field mapping is laborious (expensive) and requires highly trained personnel to correctly identify karst and synthesise the information. In the development of conceptual models of karst aquifers, the application of conventional hydrogeological methods is insufficient and can have disastrous consequences. The general vulnerability of karst aquifers, coupled with their complexity, often gives rise to problems with groundwater management in these areas.

Optimal management of karst groundwater in Ireland requires an informed understanding of the workings and vulnerabilities of the karst system and its relationship to associated surface waters and ecosystems, specific to Irish conditions. This understanding begins with an accurate map of karst features.

GEOLOGICAL SURVEY IRELAND’S KARST DATABASE

Studies of Irish karst landscapes have always been forthcoming from the classic, renowned karst regions of the Burren (e.g., among others, Williams, 1970; Drew, 1992) the northwest limestone plateaux (e.g., Kelly, 1989; Thorn *et al*., 1990), the western lowlands (e.g., Coxon & Drew, 1986; Drew & Daly, 1993) and the southern region (e.g., Gunn, 1982; Ryder, 1984), but by the mid-1990s a review of Irish karst literature indicated that there was little in terms of a systematic catalogue of the diverse features of Irish karst at local scale. There had been some efforts to list and inventory caves (Scharff *et al*., 1906; Coleman, 1965) but the distribution of other karst landforms at local scale, and their size, frequency, and spatial pattern, was somewhat undiscovered.

The 1990s in Ireland showed an unprecedented level of economic growth, with road engineering entering a new phase with the construction of Ireland's first motorways (75 % of the total length of motorway in Ireland is underlain by limestone). Buildings projects also ramped up in terms of scale, with Celtic Tiger expansion and the requirements for Environmental Impact Assessments meaning the quest for geo-environmental data was unprecedented in this country at that time. Large-scale mines had also recently been opened in Galmoy, Lisheen and Navan, all with karstic nuances and sometimes an element of karstic controversy (Dhonau & Wright, 1998). Further from this, increasing use was being made of groundwater from limestone aquifers, and with the heightened awareness of groundwater protection then-evident (e.g., Daly, 1985), the extent and significance of karst and its detailed occurrence was essential. In 2007, at the height of Celtic Tiger expansion, the then Department of Communications, Environment and Natural Resources made key datasets created by Geological Survey Ireland free for use by all stakeholders. This was intended to stimulate the environmental, construction and geoscience sectors, and to increase the base level of geoscientific knowledge. This move also aimed to provide an abundance of quality data for sustainable development and the planning of large infrastructure projects. Thus, Geological Survey Ireland's national karst database was published via interactive web mapping.

KARST FEATURE DATABASE

The karst feature database began as two separate entities, both completed as part of ground-breaking research by Morgan Burke for his MSc thesis between 1996 and 1998 (Burke, 1998). The first, 'Karst Reference Database' was an inventory of titles of articles, papers and other publications that discuss or are relevant to Irish karst. The database was collated using Microsoft Access and could be searched by author names, journal names, publishers, and other relevant thematic keywords, as well as using fields which are standard for most reference databases (Burke, 1998). The second, 'Karst Features Database' was the first to collate empirical data on the location, spread and types of karst features in the Irish landscape. Point features included springs, swallow holes and estavelles, and areal features included enclosed depressions, dry valleys, turloughs, superficial solution features and caves. At that time there was a record of 547 caves, 680 springs, 410 enclosed depressions, 353 swallow holes and 241 turloughs in the Republic (Burke, 1998). As can be observed from the numbers, this was in no way exhaustive, but was a good start!

One of the key recommendations of Burke (1998) was that the database be integrated into a Geographical Information System (GIS), a technology which was then in its infancy in terms of use and manipulation, at the time, in State bodies in Ireland. Then, the features logged in the database included grid references, but there was no way to display them as points or areas on a base-map. The integration into a GIS happened in subsequent years in Geological Survey Ireland in the early 2000s, and features were continually added to the database as they were submitted by consultants and academics working in the field. In 2000, the Karst Working Group, which included representatives of Geological Survey Ireland, the Geotechnical Society of Ireland, the International Association of Hydrogeologists (Irish Group) and the Irish Association of Economic Geology, published *The Karst of Ireland*, a booklet that explained the concept of karst and illustrated it beautifully in layman's terms. The next significant phase of data collection and population of the database was initiated in the mid-2000s, during work on the Roscommon Groundwater Protection Scheme.

Since then, occasional surges of data input have occurred when detailed source protection studies have been undertaken by the Environmental Protection Agency (2008-2014) and the National Federation of Group Water Schemes (2015-2022), as well as in detailed catchment-scale studies for geo-environmental research (Kelly & Meehan, 2010). Further input from consultants working on karst throughout the country have also bolstered the point data details. Any karst information collected by Geological Survey Ireland's own projects and activities has also been input regularly, with a large amount of karst feature mapping undertaken by the Groundwater Vulnerability Mapping project (2008 – 2013) and the GW3D project (2015–present). In 2015, Geological Survey Ireland funded the compilation of similar karst databases in Northern Ireland. This work was led by the Geological Survey of Northern Ireland and resulted in the first all-island karst landform and water tracing databases. These were published in 2016 with an additional 820 karst landforms and 69 tracer lines added for Northern Ireland. With regard to planning, the karst feature database is now a national key reference database, meaning it must be consulted as part of any Environmental Impact Assessment Report.

WATER TRACING DATABASE

Stories of water tracing involving the use of chaff or hayseeds have been passed down for generations in many parts of Ireland, but it wasn't until the early twentieth century that the first scientific water tracing experiment was conducted. Although many water-tracing experiments have been carried out in Ireland since, the literature is hard to find, often located in obscure caving journals. In 2007, Geological Survey Ireland established a national database compiling and detailing water tracing experiments, to serve as an inventory of known water tracing experiments and to store details of the traces. Data are compiled from numerous sources including maps, academic and caving journals, company reports and personal communications. The database contains specific details for each tracing experiment. There are 20 fields, which can be searched and queried by a certain topic, locality, or catchment. The database is populated with all known traces and currently contains details of more than 569 individual water traces. The database is also designed to complement the existing karst landform database.

RECENT IMPROVEMENTS AND ADDITIONS TO THE DATABASE

Geological Survey Ireland conducted a review of the karst databases in 2019 with a view to improving and updating them. Karst data have been compiled from a wide variety of data sources, some with very sparse information and/or poor locational accuracy. Since its creation, the database has been added to on an ad-hoc basis with varying levels of coverage, attribute detail and accuracy. We are fortunate to receive karst landform data sent in by groundwater consultants and engineers working on various projects. However, these datasets often require modification before they can be uploaded to the karst database, and over time this has resulted in inconsistencies within the database. Several data legacy issues were identified, and a review of international examples of karst feature databases was conducted. A new structure was proposed and developed for the database.

The new database will be divided into three categories of landforms based on their areal extent. Dry valleys, losing streams and cave passages will be displayed as linear features (polylines in GIS); larger enclosed depressions such as uvalas, poljes and turloughs will be displayed as polygons, and the remaining landforms will be displayed as point features. These three landform categories will have the potential to be linked, e.g., a cave polygon in plan view will be linked to all the cave entrance points and depressions (points and polygons) related to it. It is also proposed to indicate via a shaded colour change whether any feature has been field-verified or not. This work is underway.

NEW: TURLOUGH DATASET

The turlough polygon dataset is the first new dataset to be completed as part of the karst database overhaul and will shortly become available through Geological Survey Ireland's webviewer (gsi.ie). The GWFlood project installed monitoring stations at over fifty turloughs between 2016 and 2019, twenty of which remain in place as permanent telemetric monitoring systems. The data collected at these stations represents the largest repository of turlough hydrometric information, and it is available to view and download at Geological Survey Ireland's hydrometric viewer (gwlevel.ie).

The extents of a total of 827 turloughs are now delineated, and this new dataset was compiled from the following sources: pre-existing turloughs from the karst feature database; turloughs identified as part of the GWFlood project; NPWS databases; NPWS SAC/SPA datasets; aerial photographs; and six-inch maps. 552 of these extents are based on the 'Ten Year' flood extents calculated during the GWFlood project (McCormack et al., 2020), and the remainder are delineated by eye using the 'soft sediment' extents from Quaternary sediment maps, and re-digitised using high-resolution aerial photographs.

In addition to the online maps, we have developed data sheets for each site that summarise the main hydrometric properties of the turlough. Information on stage, volume and flood area is presented as well as an analysis of net discharges into and out of the turloughs during filling and emptying periods respectively. These sheets are available to download at gwlevel.ie or on the GSI webpage, and they will soon be made available through the GSI karst database viewer.

UPDATED: WATER TRACING DATABASE AND KARST FEATURE DATABASE

The water tracing database has undergone a systematic review since end-2019 to remove inaccuracies due to legacy data and input errors. This database currently contains details of 569 traces, all of which have been checked, updated, and improved. Figure 1 shows examples of some of these updates.

During this work, manual checks of modern aerial photographs and older maps revealed inaccuracies in the karst feature database that were subsequently corrected. A total of 2,198 landforms have been added or improved, with 836 moved to the correct location and 1,362 previously unmapped landforms added to the karst database. (The locational accuracies of the remaining karst landforms in the database will be progressively checked and updated in the future.) The population of the new karst databases (with improved structure and three feature categories) has also commenced, with 57 dry valleys now delineated as linear features, 70 cave plans now added as linear features, 27 uvalas delineated as polygons and 19 new sinking stream segments added.

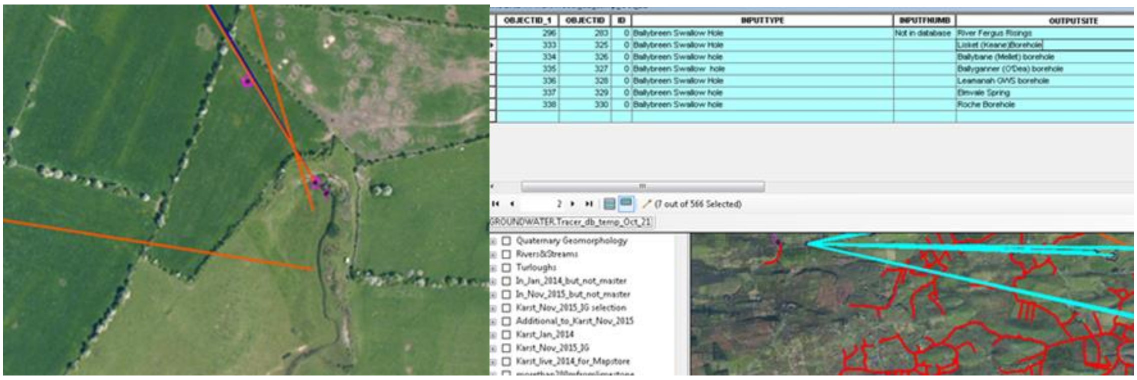

Figure 1 *Examples of some of the improvements to the new karst tracer database, left: multiple lines starting at different points and not properly linked to a karst landform feature, and right: filling in of missing attribute data.*

APPLICATIONS AND IMPACTS

Geological Survey Ireland has long recognised the complexities of Irish karst hydrogeology, and consequently the karst feature maps are an integral part of Irish Groundwater Protection Schemes. Geological Survey Ireland's aquifer map distinguishes between limestones with and without a high degree of karstification. All limestone categories, depending on their permeability, storage capacity and areal extent, are categorised into Regionally Important (R); Locally Important (L); and Poor Aquifers (P). Regionally important limestone aquifers are subdivided into three categories. Where karstification is slight, the limestones are hydrogeologically similar to fissured rocks and are classed as Rf. Aquifers in which karst features are more significant are classed as Rk. Within the range represented by Rk, two sub-types are distinguished, termed Rkc (conduit flow dominant) and Rkd (diffuse flow dominant) (Daly, 2002).

The karst feature database is incorporated into the National Groundwater Vulnerability map, as this map records locations where infiltrating recharge waters may be by-passing overlying protecting layers. To protect groundwater receptors it is recommended that influent karst landforms are given at least a 30 m buffer zone. A sinking stream should have a 30 m buffer zone at the point of sinking or along the length of the losing stream section, and the whole stream upstream of this point should be given a 10 m buffer zone. To facilitate this, a 'sinking streams' database was created to record all reaches of streams and rivers that sink underground into karst.

Karst aquifers are also considered in groundwater source protection zone delineation. Due to the nature of the fast flow in conduit-dominated karst aquifers, all of the ZOC to a spring or borehole is within the Inner Protection Area (SI), which is the area defined by 100-day time of travel.

Geological Survey Ireland's karst database is critical as a source of information for land surface zoning within Groundwater Protection Schemes, as well as providing key data for consultation as part of the planning process. The following are a few examples of how the karst database has provided a foundation for the development of new projects.

RATHCROGHAN DRINKING WATER SOURCE MANAGEMENT

Intensive karst mapping in Roscommon and the Rathcroghan Uplands (Lee and Kelly, 2003; Hickey, 2008), including the availability of LiDAR data, meant the karst database was reasonably well populated for this area. Consequently, there was a good provisional conceptual understanding of the workings of the karst aquifers here. This provided a good foundation for delineating desk based ZOCs for five Group Water Schemes (GWSs) in the area, as part of a national programme (Kelly *et al*., 2015; Meehan *et al*., 2015). This work was carried out by consultants for Geological Survey Ireland in collaboration with the National Federation of Group Water Schemes (NFGWS). Uncertainties in the desk based ZOCs, coupled with the often-poor drinking water quality, provided a reason for Geological Survey Ireland and NFGWS to secure additional funding from DEHLG to carry out further investigations. Multi-dye tracing investigations were undertaken to establish geoscientific ZOCs for all the water supplies in the area (Duncan et al., 2015, 2016). The results provided sufficient information to enable ZOCs to be delineated with some confidence, and the creation of site-specific conceptual models. These conceptual models have enabled NFGWS and Geological Survey Ireland to establish a new pilot project, including all of the Rathcroghan GWSs, to establish an Integrated Source Protection Plan (ISPP) to protect the source water, and centres on communicating and working with the stakeholders to raise awareness of and address contamination issues within the catchments through effective implementation of appropriate land management measures (Kelly & Dillon, 2020; Kelly *et al*., 2021). Furthermore, the NFGWS with partners from the pilot projects, including Geological Survey Ireland, established a Framework for Drinking Water Source Protection (NFGWS, 2019). This forms a standardised approach to evaluating raw water, characterising catchments to surface water and groundwater sources, and establishing a plan to protect the source and/or manage the significant risks within the catchment.

LOUGH CARRA

Lough Carra, a groundwater-fed marl lake in Co. Mayo, is celebrated for the exceptional rarity of its ecological communities. It is a source of drinking water and a wild trout fishing lake; it forms part of the Lough Carra/Mask Complex SAC. The quality of the lake water has been in decline over recent years and the new LIFE Lough Carra project consortium was developed to tackle this problem with tailored nutrient management measures for the catchment. Geological Survey Ireland are partners in this project and will carry out a detailed hydrogeological investigation over the next three years (2021 – 2024), with the main aim of accurately delimiting the groundwater catchment to the lake.

Geological Survey Ireland had already undertaken a significant programme of field mapping of karst features around Lough Carra in 2019 as part of the GW3D project and so were natural partners for the LIFE project. This work consisted of a detailed desk study using remote sensing data to identify features of interest, followed by intensive field mapping and ground-truthing of features. Engagement with locals and landowners was a valuable source of information, and thermal imaging was successfully used to identify karst features such as subaqueous springs. This study covered an area of around 200 km^2 (the surface water catchment is currently estimated at around 110 km^2) and in total 693 new karst features were identified and added to the karst database. The vast majority of these (574) were dolines or enclosed depressions, and the study also identified 66 springs/holy wells, 15 swallow holes, 3 sinking streams and 8 potential turloughs that were previously un-recorded. Geological Survey Ireland will build on this work with multi-dye tracer testing commencing in 2022. The results of this work have already been of value to the development of an ISPP for the Lough Carra GWS (work carried out by CDM Smith on behalf of NFGWS in 2021).

FLOOD SCHEMES IN GALWAY AND MAYO

In some cases, Geological Survey Ireland's priorities for enhancing the karst database can be informed by the requirements of Local Authorities. For instance, in 2018 Geological Survey Ireland was requested by Galway County Council to carry out a tracer study as part of investigative works under the South Galway Flood Relief Scheme. Also in 2018, Geological Survey Ireland was approached by Mayo County Council to carry out a tracer study as part of a flood scheme feasibility study for The Neale (Kelly *et al*., 2018). In both studies the objectives of the traces were to improve the conceptual understanding of the karst catchments and thus inform the design of the proposed flood relief schemes. The traces were planned and executed by Geological Survey Ireland using existing and new karst field data in consultation with the appointed contracted engineer for the flood schemes, Ryan Hanley in both cases.

FUTURE WORK

The existing karst feature database will be scrutinised for inaccuracies and progressively updated over the next year. The value of accurate karst mapping to the community and general economy is well established, as a deep understanding of karst hydrogeology is needed to protect groundwater resources, understand groundwater flooding and avoid induced subsidence due to karst collapse. Karst mapping and tracer testing is costly and time consuming, and traditional methods of karst mapping have been slow and labour-intensive. With new advances in remote sensing (high resolution satellite photography, LiDAR) and machine learning, Geological Survey Ireland is exploring the benefits of both as we continue to add new data to the karst database.

Improvements in mapping technologies, and the existence of multiple quality datasets for a single region, have made it easier than ever to identify potential karst features in a desk study, before verifying the features in the field. It may be possible to use multiple datasets (even seemingly unrelated ones) in an automated machine learning process to identify karst features, and even determine karst formation susceptibility, or the susceptibility of an area to experience karst collapse or subsidence. Preliminary (unpublished) academic studies on this theme and potential methodologies have shown promising results. It will still be necessary to ground truth features to calibrate these models, but it is anticipated that this will allow more efficient deployment of human resources into the field.

We are certain that it is evident to anyone working in this field that there are vast numbers of karst features in Ireland that remain unseen and unrecorded. It is our ambition to steadily increase and enhance the national karst database using all available tools at our disposal. In particular we appeal to our stakeholders in the geotechnical community, who may have conducted their own karst mapping exercises in the past, to contribute their data to the national database, and continue to help us to make the invisible visible.

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BRINGING GROUNDWATER BACK INTO PUBLIC SUPPLY

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ABSTRACT

Public water supply in Northern Ireland is sourced almost entirely from surface water. Recent drivers, such as increasing network resilience to cope with the effects of climate change, reducing greenhouse gas emissions and energy costs have convinced Northern Ireland Water Ltd. to consider the innovative role that groundwater could play in helping to address these drivers.
Bringing groundwater back into public supply is a challenge and this paper details some of the lessons that have been learned by the engineers and hydrogeologists involved in this project over the past four years. This paper aims to be a helpful reference for hydrogeologists involved in bringing groundwater into an already established public water supply network.

Key words: *Public water supply, Northern Ireland, Groundwater, Borehole, Spring, Yield, Water treatment.*

INTRODUCTION

In 2004 following recommendations from the 2002 Water Resource Strategy (Water Resource Strategy 2002 – 2030), Northern Ireland Water Service (as it was known then) made the decision to rationalise a number of its water supply sources. The rationale for the decision was made following a review of all sources, at which time a number were identified as being both high cost to operate and also presented a higher risk of water quality issues. There was a drive at the time by Senior Management for a more centralised Water Supply Network. Preference was given to water supply sources which could yield high flow rates so that large water treatment plants could be upgraded or installed. At the time there were 51 existing sources (13 boreholes, 19 impounding reservoirs, 10 natural lakes, 5 river abstractions, 3 springs, and 1 pumped storage). It was recommended that 24 of these sources be decommissioned, which included all 13 boreholes and 3 spring sources. At one stage, groundwater was supplying 126 Mld^{-1} of a total 700 Mld^{-1} (18 %) (Robins, 1996). Individual delivery yields ranged from 0.05 Mld^{-1} to 5.6 Mld^{-1}. Today, groundwater supplies 0.25 Mld^{-1} at one site (Rathlin).

Groundwater is a hidden asset with many positive qualities. It can be accessed locally to where it is needed, reducing requirements for pumping and therefore energy costs. It often has very good quality and requires little treatment to ensure it meets drinking water standards and being suitable for potable supply. It is more resilient to extreme weather events and contamination on the ground surface. Since 2016, the Geological Survey of Northern Ireland have been advocating to Northern Ireland Water for the role groundwater could play in Northern Ireland's public water supply network. In 2018, Tetratech (previously WYG) were appointed as consulting hydrogeologists to investigate the viability of groundwater being used to address some of the short-term and long-term water supply resilience and efficiency issues that NI Water have identified.

These past four years have been a journey of learning for everyone involved. This paper documents some of those learnings for the benefit of other hydrogeologists and water professionals who may someday find themselves working to bring groundwater back into public water supply.

DRIVERS FOR INNOVATION

CLIMATE CHANGE

Weather and climatic conditions are changing globally and Northern Ireland is not exempt from these changes. Over the last four years, NI WATER has faced three high demand and drought incidents. These high demand incidents are often driven by extended periods of long dry warm which leads when consumers use more water including irrigating gardens and filling various types of pools for recreation.

In July 2021 demand rose by 30% over a period of 10 days. These high demand events put a strain on water supply systems and require Water Treatment Works (WTW's) to operate at or close to full capacity.

Drought incidents occur when a source of raw water becomes depleted. One such example is when water levels in Spelga Impoundment reservoir in the Mourne Mountains (County Down) reaches low levels and exposes an old road and bridge that were flooded after the dam was constructed.

The intensity and frequency of high demand and drought incidents is such that NI Water plan for these events. This is therefore a key driver towards identifying innovative ways to boost the resilience of their water supply network. Groundwater sources could be one such solution.

The identification of stressed areas allows groundwater water resource evaluation to become more targeted. Investing in a programme of exploratory drilling and testing provides the lines of evidence required by the water utility company and regulators alike that the introduction of groundwater into the network at strategic locations can enhance water supply resilience, often at a lower capital and operational cost than alternative solutions. Some options currently being considered by NI WaterNI Water include:

- Pumping groundwater from boreholes close to a lake or impounding reservoir, which supplies a WTW, to maintain water levels and ensure the WTW can operate at its full capacity.
- Pumping groundwater from boreholes close to a WTW with available capacity, so that groundwater can be fed directly into the works or into raw water mains.
- Exploratory drilling and testing at or near to existing service reservoirs with new localised treatment solutions. Groundwater can then be used to 'top-up' the service reservoirs, thus freeing up capacity at the WTW so that water can be directed to other service reservoirs, therefore boosting the whole network resilience (Figure 2).
- Putting potable groundwater directly into mains. This reduces the flow rate out of service reservoirs and helps maintain pressure with the mains.

ENERGY

Water abstraction and treatment can require high energy consumption. Energy is one of the largest operating costs for NI Water and there is a focus on reducing these costs without compromising quality and customer service. To achieve this more efficient delivery of drinking water is much sought after. As the carbon agenda has grown, so too has NI Water's desire to drive down carbon and reduce the use and cost of energy. NI Water are committed to reducing its carbon emissions by 50% by 2030 and to be carbon neutral by 2050. To reduce energy costs and usage, there is a need for NI Water to continue to optimise operational activities water treatment and supply. The identification of strategically located, high yielding, high quality groundwater sources can help NI Water meet this target.

Figure 2: *Site inspection at an exploratory borehole and pumping test rig beside an existing service reservoir*

LESSONS LEARNED

Over the course of the last four years, various lessons have been learned as consideration has been given to how groundwater could address some of the drivers detailed above.

YIELD VERSUS QUALITY

At the start, from a hydrogeologist's perspective, acquiring a groundwater supply which required little or no treatment was considered more important than the yield that could be achieved. However, the NI Water engineers were mainly focused on yield. A number of lessons have been learned in this regard:

- All raw water requires treatment – NI Water meet the strictest water quality drinking standards and therefore no matter how good the source is it needs a robust low opex water treatment system or go through an existing WTW.
- A low opex treatment solution often requires high capex - Capital in the current times is not easily secured with competing demands and priorities.
- The more water that can go through a treatment solution the likelihood is the more economical the business case will be - Therefore yield becomes very important and effectively a deal breaker. Aquifers with lower potential (i.e. less than 1 Mld^{-1}) are generally screened out early for this reason.

Whilst it is sensible to assume that some form of treatment solution will be required, this does not mean that aiming to acquire a good quality groundwater that requires little or no treatment should not be pursued. Less reliance on treatment solutions will ultimately require less energy, less space, less chemicals, less operational maintenance and will be more economical overall. Other measures, such as catchment delineation and source protection zone risk management should also be used to ensure high quality water is supplied to customers.

WORKING WITH EXISTING INFRASTRUCTURE

In an ideal world, designing a water supply system from scratch to meet the current and future demands would be great. The reality is that the infrastructure that exists, is not likely to be replaced soon. This means working with what already exists such as where WTW, mains and service reservoirs are located. This can be frustrating, especially when there is a good potential groundwater source, but no feasible way to integrate it into the existing network.

For groundwater sources to be considered, they must outperform existing sources and infrastructure that are already in place. It is therefore best to focus on the cases where the cost of delivery to consumer is high and high demand incident resilience is low. A business case is therefore more likely to be successful as the cost savings and the carbon savings can be more convincing.

SAND AND GRAVEL VERSUS BEDROCK AQUIFERS

Early on, the advice being given to NI Water was to avoid sand and gravel aquifers and focus on bedrock aquifers. The rationale was that sand and gravel aquifers are more vulnerable to contamination than bedrock aquifers and the hope was for NI Water to have positive experiences with groundwater as they took baby steps back towards it.

However, experience has found that since borehole yield is a major factor that influences business cases, boreholes in sand and gravel aquifers can often deliver very high yields and if located close to an existing WTW with capacity, a business case will stack up very well. Therefore, sand and gravel aquifers close to WTW are key target aquifers for feasibility assessments.

EXPLORATORY DRILLING AND PUMPING TESTS

Like any engineering project that involves working with the ground, a project should begin with ground investigation works. In the case of new groundwater supplies for public supply, this means exploratory boreholes. A review of the Geological Survey of Northern Ireland archives found that during the 1970's and 1980's when many of Northern Ireland's former water supply boreholes were constructed, typically five exploratory boreholes were drilled for every one production borehole that went into service.

Following a desk study, exploratory drilling combined with pumping tests and water quality analysis provides the lines of evidence upon which a business case for a new source can be made. New production boreholes can then be properly designed and constructed knowing the depth to bedrock, resting water level and the main inflow zones.

Experience so far has found that skipping the exploratory phase and going straight to drilling new production boreholes is a gamble and can lead to disappointing and expensive results which do not cast a positive light on groundwater supplies.

FORMER PRODUCTION BOREHOLES AND PUMPING TESTS

Rather than drilling exploratory boreholes, start with what already exists. If former production boreholes still exist, the cost of opening them up, doing a downhole camera survey, possibly some rehabilitation followed by pumping tests, is a relatively inexpensive way of identifying if the same boreholes could be brought back into supply, or new, more modern production boreholes should be drilled. If they worked before, then there is a high chance they will work again (Figure 3).

Existing production boreholes have other positive attributes also. They generally have an existing electricity supply, the land might still be available and the landowner is more likely to being amenable to selling more land, if required. Also, the supply mains may still be in place. These can be surveyed and may need little or no rehabilitation to bring them back into service. Where such conditions exist, the level of capital investment required for a new groundwater source becomes an attractive prospect and strengthens the business case.

Figure 3: *Inspecting a former production borehole*

AVOID SPRINGS

Springs were very popular in the past. No drilling was required and nature was delivering groundwater direct to the surface. However, springs are in effect streams and rivers and taking water from them will have a direct and immediate impacts on low flows. With abstraction licensing systems in place, acquiring a license to abstract from a spring can prove more difficult. Granted, pumping groundwater from a borehole will ultimately result in an impact on river flows somewhere, the effect is less likely to be as direct and immediate.

Another issue with springs is that a collection chamber is required and this may be located downstream of the actual spring. This provides opportunity for contamination prior to abstraction.

In some cases, subject to the hydrogeology, a nearby borehole may be a better solution.

THE VALUE OF PUMPING TESTS

Pumping tests are an excellent tool for the hydrogeologist to answer the key questions that engineers require; what yield can be achieved, is this yield sustainable, what water features this impact and by how much, can another borehole be drilled and what treatment requirements are there (Figure 4)?

Figure 4: *Pumping test rig setup on a former production borehole*

A desk study can go part way to answering some of these questions, but a contemporary, well run pumping test on a site of interest will provide much more reliable and convincing answers to these questions. This is what engineers require. Therefore, if involved in such projects, from early on, advise that pumping tests (step drawdown and constant rate typically as a package) on existing boreholes or new exploratory and production boreholes should be performed.

STAKEHOLDERS

To bring any new or redundant groundwater source back into service requires various permissions, licenses and approvals:

- Water Order Consent (either new or amendment)
- Drinking Water Inspectorate (DWI) consent
- Abstraction licence
- Possibly an electricity connection upgrade
- Telemetry signals approval
- Rivers Agency Schedule 6 Consent
- Planning Approval
- Effluent consent (depending on the size of treatment works)

Early engagement with stakeholders is therefore important to ensure that all these are in place prior to a new source becoming operational.

BAN ON MILD STEEL

In 2021, the Drinking Water Inspectorate issued a letter informing NI Water that following a review, mild steel must not be used in borehole construction and components for abstraction from boreholes.

Mild steel has been used commonly in the drilling of boreholes as conductor casing to prevent the collapse of shallow sediments into the borehole during drilling. This is often left in place after drilling is completed but should be jacked out of the ground before cement grout has set. Therefore, contracts issued for the drilling of any boreholes that could be used for public water supply production must include provision for mild steel to only be used as a temporary measure during drilling. This has an influence on the size and type of drilling used, as it must be capable of jacking the conductor casing out of the ground.

CONCLUSIONS

- Groundwater abstraction sources could be an innovative solution to address some of the challenges that climate change and the need to reduce greenhouse emissions present to public water supply systems.
- A new water source must have a high yield (>1 Mld^{-1}) for any capex business case to stack up.
- Integration into existing infrastructure is vital. A promising aquifer with no existing water supply infrastructure will require more capex.
- Sand and gravel aquifers, if located close to existing water supply infrastructure can potentially provide high yields and may be a more viable option than bedrock aquifers despite being more vulnerable to contamination.
- Exploratory boreholes reduce project risk and should be drilled during a feasibility study stage rather than aiming to drill a production borehole following a desk study.
- Springs are best avoided. They are effectively surface water sources and the impact on low flows of first order streams will likely be unacceptable to acquire an abstraction license.
- Pumping tests reduce project risk and can add a lot of value over and above a desk study.
- There are many stakeholders that have a say over whether a new groundwater source can start operation. It is important to engage with these stakeholders early to determine what information they require.

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IMPROVING THE UNDERSTANDING OF CURRENT AND FUTURE GROUNDWATER RESOURCES: GW3D AND GWCLIMATE

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ABSTRACT

Geological Survey Ireland (GSI) is committed to providing free, open and accurate data and maps on Ireland's subsurface. GSI's Groundwater and Geothermal Unit data and maps underpin policy in a number of sectors such as planning, agriculture, water resources and climate action. These data provide a better understanding of hidden groundwater resources thus making the invisible visible.

This paper will focus on two on-going Groundwater and Geothermal Unit projects: GW3D and GWClimate. The GW3D project is a regional assessment of potential groundwater resources across 32 catchments in the east of Ireland. These assessments develop an initial hydrogeological conceptual model for the catchments and provide a basis for prioritising further investigation into groundwater resources. Progressing on from the aquifer and vulnerability map, the assessments include data on anthropogenic settings, climate change, groundwater and surface water pressures to create a conceptual model of each catchment's potential groundwater resources.

The GWClimate project is a groundwater monitoring and modelling project that aims to investigate the impact of climate change on groundwater in Ireland. The data and analyses from this project will improve the national capacity to understand how groundwater resources respond to climatic stresses and enhance the reliability of planning and forecasting.

GW3D

Irish groundwater resources support drinking water supply, industry and agriculture. Sixteen percent of Ireland's public water supply is sourced from groundwater; that percentage increases significantly in certain counties (for example 95% in Laois, 75% in Offaly and 61% in Roscommon). In addition, groundwater also forms an integral part of the water cycle and supports river flows, lake levels and ecosystems. With increasing population, supply – demand deficits and the impact of climate change, there is a need to better understand Irish groundwater resources for drinking water supply.

For that purpose, GSI's GW3D project has been carrying out regional scale groundwater resources assessments in 32 catchments in the east and south of the country (Figure 1). The methodology comprises four steps: 1) Identify the groundwater resources within each catchment; 2) Identify any potential constraints to those groundwater resources; 3) Compare across all the catchments and prioritise; and, 4) Carry out fieldwork to verify and quantify resources.

Figure 1: *Catchments included in the GW3D study area*

Groundwater resources within each catchment are assessed using all relevant, readily available information, such as meteorological, geological, hydrogeological (Figure 2) etc. These data are used to produce a conceptual model and water balance (Figure 3) for each catchment. The potential constraints to future groundwater abstractions which are considered include: 1) hydrogeological considerations; 2) ecological considerations; 3) existing abstractions; 4) groundwater chemistry; and, 5) impacts of climate change.

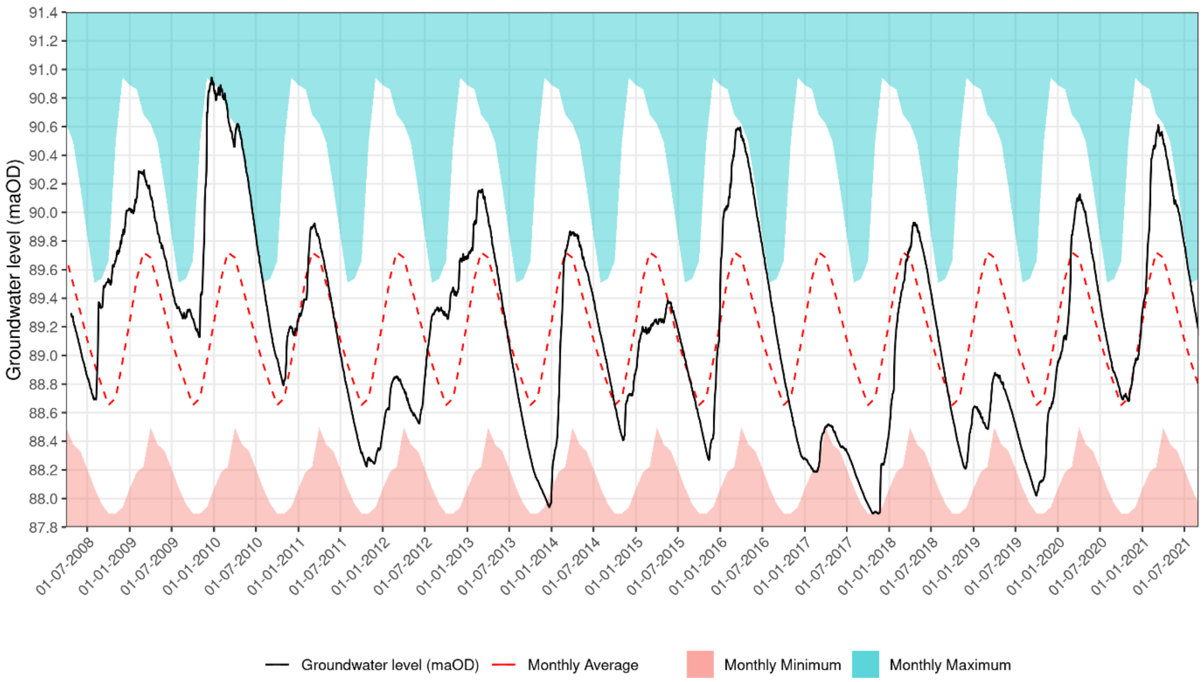

Figure 2: *Hydrograph for EPA monitoring borehole MB29 located east of Kildare town in the Curragh sand and gravel aquifer.*

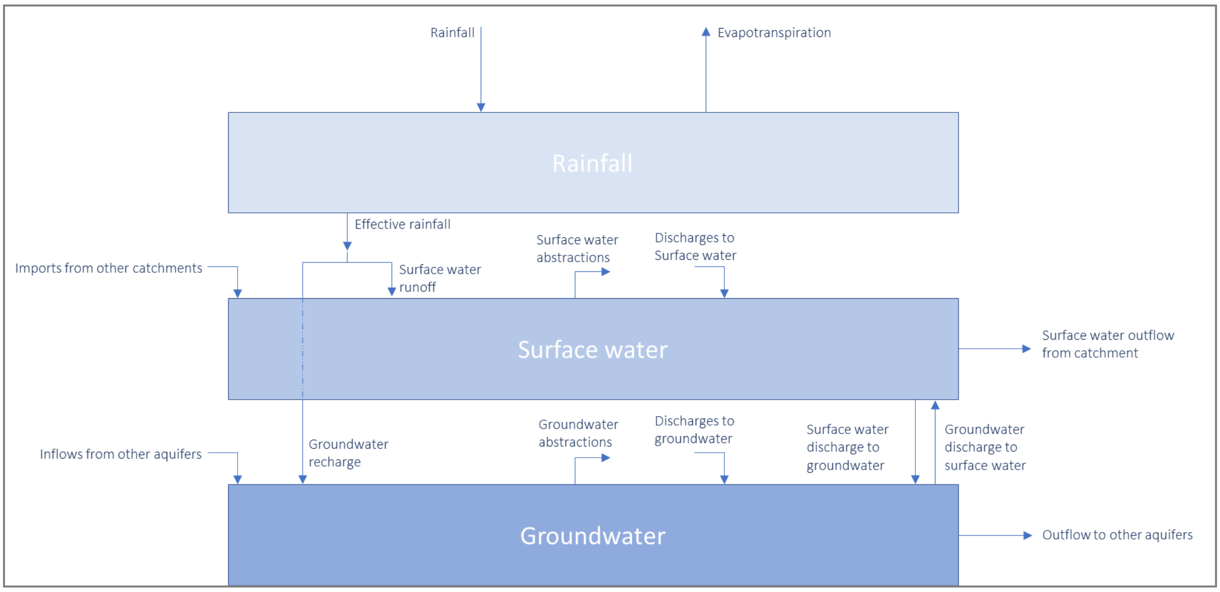

Figure 3: *Schematic representation of the water balance assessment*

The areas with promising groundwater resources and without potential constraints to future groundwater abstractions are identified within each catchment. The results of each catchment are compared across the catchments to identify the areas with the best groundwater resources in the east and south of the country. This information will allow water resource managers to consider the best areas for future groundwater abstractions. The final step of the methodology is to install monitoring boreholes to test the outputs of the desk study. GSI is currently exploring sites in the Barrow and Slaney catchments.

The hydrogeological resources assessments for catchments in the south and east of the country will shortly be available to download from www.gsi.ie.

GWClimate

Climate change is likely to have a major impact on Ireland's water resources and environment in coming decades. It will pose significant challenges to how groundwater is currently managed, with exacerbated seasonal flooding and drought being forecasted that will increase pressures on maintaining water supply, quality and biodiversity. Monitoring and early detection of these pressures is key to informing successful adaptation strategies to minimize adverse impacts. In this context, Geological Survey Ireland, in collaboration with the Institute of Technology Carlow has initiated a new project: GWClimate.

The project expands the existing national monitoring capacity towards relevant climate change processes, notably by: 1) developing analytical approaches to evaluate the susceptibility of groundwater systems to climate processes; 2) establishing a long-term strategic groundwater level monitoring network; and, 3) developing groundwater models to predict future impacts from climate change.

EVALUATING GROUNDWATER SUSCEPTIBILITY TO CLIMATE CHANGE IMPACTS

GWClimate is evaluating the susceptibility of groundwater to climate change impacts in the context of both groundwater drought and groundwater flooding. Recent work has focussed on investigating groundwater drought using two approaches: 1) investigating drought susceptibility based on the concept of "groundwater memory"; and, 2) using the Standardised Groundwater Index to characterise groundwater droughts over time. This ongoing work is summarised below.

The susceptibility to groundwater drought is being investigated based on the concept that low-storage aquifers are less resilient to drought than high-storage aquifers. As proxy for storage, the 'memory effect' has been determined for 133 groundwater level time series (from EPA & GSI records) across Ireland. The quality of the memory is expressed by the autocorrelation function (ACF) (Schuler et al., 2020), notably at which lag time the ACF reaches below a threshold of 0.05. Following this, the lag time across the Republic of Ireland was simulated using the Random Forest machine-learning algorithm, using national digital maps as input files (Figure 4).

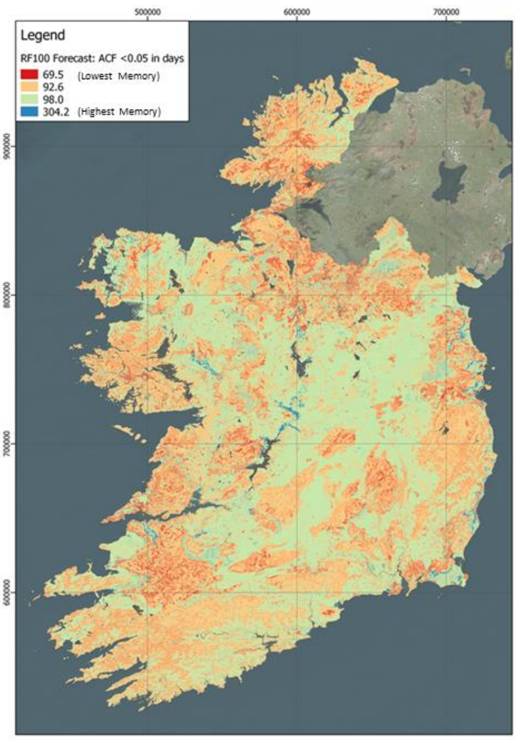

Figure 4: *Simulated lag times (days) for the Autocorrelation Function of groundwater level time series until reaching below 0.05, classified into four groups. Lowest lag times (red) indicate lowest memory, quickest response of hydrographs to rainfall or drought, and hence, potentially highest susceptibility of groundwater to drought (and conversely).*

In addition to the autocorrelation analysis, GWClimate is working to characterise groundwater droughts in Ireland by applying the Standardised Groundwater level Index (SGI). This index, developed by (Bloomfield and Marchant, 2013) is a non-parametric approach which normalises groundwater timeseries allowing for comparison across sites. Through the GWClimate project, the SGI is being calculated for all available groundwater time series (see Figure 5 for an example SGI time series).

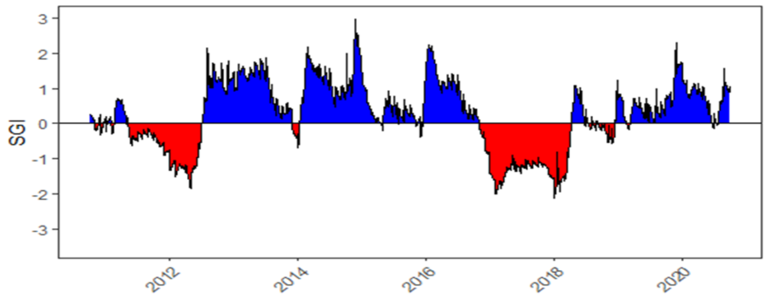

Figure 5: *Sample SGI Time series from the EPA Druids Glenn monitoring station, Co. Wicklow. Blue values indicate relatively high groundwater levels and red values indicate low/drought groundwater conditions.*

MONITORING IMPACTS OF CLIMATE CHANGE TO GROUNDWATER

This project is developing a develops groundwater monitoring network that allows assessment of specific hydrologic dynamics in the context of related climate change pressures, for the purpose of a) climate change assessment, and b) climate change adaptation. The monitoring network is being designed to represent a spectrum of hydrogeological environments and to record relevant hydrological processes with regards to groundwater drought, groundwater flooding, groundwater-surface water interaction, and sea water intrusion.

Ideal sites for recording these dynamics should have minimal anthropogenic influences, but an expected susceptibility to climate change processes as a result of the geographical location and the intrinsic properties of the bedrock and overburden. Monitoring sites will record level and temperature, and optionally also electrical conductivity (EC) if relevant. Thus far, monitoring sites have been identified in Dublin City, South Galway, Longford, Offaly and Wexford. Drilling is set to commence in early summer 2022.

In addition to the rollout of monitoring sites, the GWClimate project is further contributing to the national groundwater monitoring archive by: 1) Recovering and digitising historic groundwater level time series physically recorded on drum charts at 40 sites around Ireland between 1974 and 2017; and, 2) upgrading the GWFlood remote sensing hydrograph generation tool (McCormack et al., 2020) into a near real time system. Both of these new data sources will be made available through the GSI groundwater data webportal: https://gwlevel.ie/.

MODELLING THE IMPACTS OF CLIMATE CHANGE TO GROUNDWATER

Groundwater models are being developed for the purposes of: 1) the prediction of future climate change impacts, 2) the development of forecasting tools and 3) the reconstruction of historic data. Lumped parameter models for new and existing monitoring wells are being developed, and turlough models produced during the 2016-2019 GWFlood project (McCormack et al., 2020) are being enhanced if/where necessary.

Monitoring wells from the EPA network as well historic GSI sites are being modelled using Aquimod software developed by the British Geological Survey (Mackay et al., 2014). This software simulates groundwater-level time series at a point by linking simple algorithms of soil drainage, unsaturated-zone flow and groundwater flow. It uses time series of rainfall and potential evapotranspiration as inputs to produce a timeseries of predicted groundwater levels. Thus far Aquimod has been applied to 104 Irish monitoring sites. Approximately 40 of these models are considered as complete with suitable calibration and validation accuracy metrics, whilst calibration is still ongoing for the remainder of sites. See Figure 6 for an overview of modelled groundwater sites with a distinction between well calibrated sites (Nash Sutcliffe Efficiency greater than 0.75) and poorer/on-going calibrations.

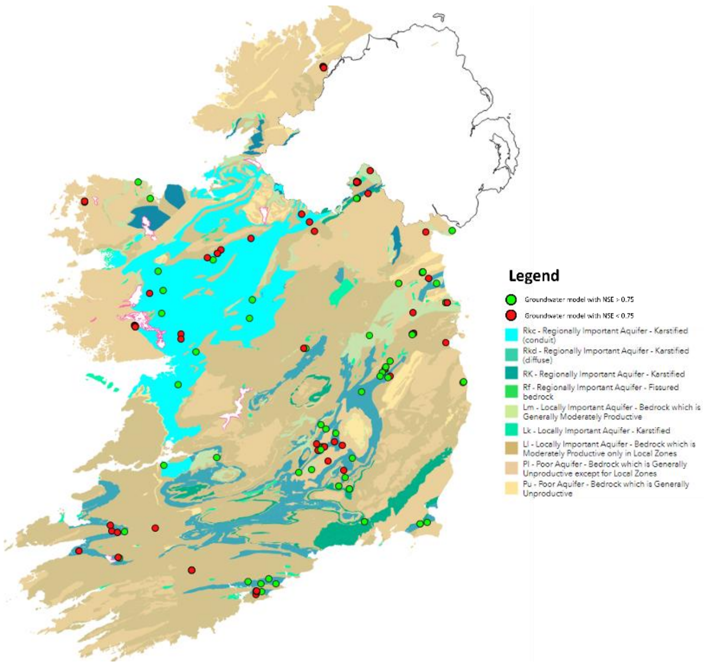

Figure 6: *Distribution of modelled groundwater monitoring points. Green points represent sites with Nash Sutcliffe Efficiency (NSE) greater than 0.75. Red point represent NSE values below 0.75.*

In addition to the Aquimod models mentioned above, GWClimate is also focussing on groundwater flood models. Through the 2016-2019 GWFlood project, 440 lumped parameter models of turloughs were developed for the purposes of predictive flood mapping. These models were based on the Antecedent Precipitation Index (API) used rainfall and potential evapotranspiration as inputs to produce a timeseries of predicted flood levels. Now, through the GWClimate project these models are being adapted in order to improve accuracy and enable the development of flood forecasting tools and climate change analysis.

ACKNOWLEDGEMENTS

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SESSION III

CREATING LIGHTBULB MOMENTS: THE POWER OF USING GROUNDWATER IN GEOSCIENCE COMMUNICTION

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ABSTRACT

Science communication is an important part of most researchers work, helping to raise awareness of what they do, and using it to educate, inspire and inform a non-specialist audience on the impact of good science. As a multidisciplinary subject, geoscience can be regarded as 'socially minded', as many elements impact directly upon the public. Groundwater is one of those areas, although it is probably one that the public is least aware of, despite the high impact it has on daily lives.

Communicating groundwater presents a real opportunity for geoscientists as everyone needs water and for the most part, most people have a fair understanding of what it is. For that reason, groundwater can be used as a tool to create 'lightbulb moments' and help the public fully understand the importance of geoscience.

Examples of such 'lightbulb moments' can be found all across the island of Ireland, delivered by numerous organisations. A selection from Northern Ireland have been chosen for this paper and include the karst model at the Marble Arch Caves, the Loughareema entry into the 100 Great Geosite Initiative and the Dynamic Dye Tracing event as part of NI Science Festival.

Groundwater has a lot to offer geoscience communication and if done well, can help to bring about a real change in the way that the general public regard geoscience as a subject.

Key words: *communication, groundwater, general public*

INTRODUCTION

Science communication is arguably the most important weapon in a researcher's arsenal. In an academic context, it helps to increase understanding and collaboration, and being able to communicate the relevance and impact of research is often a requirement of funding and will help to enhance an academic career.

Science communication is about so much more than that though as it not only helps to raise awareness of research results, it also helps to educate, inspire and inform a non-specialist audience. Increasingly, the communication of science influences people's opinions and behaviours. This has never been more obvious as it has been during the Covid-19 pandemic with science communication influencing decisions on a number of topics including whether or not to wear masks or receive vaccinations.

Communicating research to a non-specialist audience is becoming increasingly important to build support for science, and in many cases to encourage informed decision-making at all levels. This is especially important when it comes to controversial issues such as climate change and fracking, both of which are in the realms of geoscience communication.

WHAT IS GEOSCIENCE COMMUNITION?

Geoscience communication is a form of science communication that is concerned purely with the geosciences. Sometimes referred to as Earth science, geoscience is essentially the study of the Earth in all of its forms. It of course includes rocks and minerals, but also the processes that shape the Earth's surface, the range of natural resources available, and how all of these are interconnected.

CONNECTING WITH THE PUBLIC

Geoscience is an applied science, and often referred to as being interdisciplinary as it contains elements of the three 'traditional' science of biology, chemistry and physics as well as engineering and geography. Out of all the science topics, geoscience is the most 'socially-minded' with many aspects impacting directly upon the general public. This may be in the form of geohazards such as volcanoes and earthquakes, or it could be in the use of the rock record to help understand past climate change.

One aspect of geoscience that affects each and every member of the public, is the need for natural resources including those used for energy and for construction. However, there is one natural resource that is often forgotten about and that is groundwater. Used by so many for a variety of purposes including domestically for bathing, cooking and drinking, as well as for agriculture and industry, it is often a literal case of 'out of sight, out of mind'.

Instead of being seen as a challenge, this should be regarded as an opportunity, as everyone needs water and it is something that every single person can relate to. We all know what water looks like, most of us know what it is made of, and for the most part we know where it comes from. Groundwater can therefore be a useful tool in creating 'lightbulb moments', a sudden enlightenment or revelation, and could help the public fully appreciate how important geoscience is to each and every one of us.

TYPES OF COMMUNICATION

Geoscience communication is something that is attempted by many, but not always successfully. Careful consideration needs to be given to the message that you want to convey, the audience you are trying to communicate with, and of course, the best type of communication for the situation. There are a number of communication types that should be considered:

i) Physical communication: These are tangible objects that communicate a specific message including displays, signs and panels.

ii) Virtual communication: There are publications or IT-based communication resources that can be used at any location and include videos, websites and publications.

iii) Experiential communication: This is communicating through a specific experience that involves physically bringing a story to life.

Regardless of what type of communication is delivered, there are a number of key points that should always be applied:

- The message should be simple and should leave behind key pieces of knowledge in the minds of your audience.
- The content should be layered to provide for many levels of interest.

- Know your audience so that you cater to the different learning needs and interests of those listening.
- Make your message relatable so that it has immediate relevance to your audience.
- Create a story so that it links with other aspects of people's lives and makes them want to explore more.

LIGHTBULB MOMENTS IN GROUNDWATER COMMUNICATION

There are many examples of 'lightbulb moments' being used to communicate groundwater, but for the purposes of this paper only a selection has been chosen, one for each of the different types of communication listed above.

i) Karst model at Marble Arch Caves

The Marble Arch Caves in Co. Fermanagh is one of Northern Ireland's premier geotourism destinations. As part of the Cuilcagh Lakelands UNESCO Global Geopark, it works to not only bring in tourists but it also attracts educational visits from both schools and universities.

The visitor centre has undergone extensive development in the past 10 years as a result of significant EU-funding including a complete overhaul of the interior interpretation. Whilst this includes elements of groundwater, undoubtedly the most successful and enduring piece of groundwater science communication is in the form of the karst model that has adorned the wall of the lower level of the centre since the 1980s.

The model shows a cross-section through a hypothetical karst setting, although loosely based on that below the Marble Arch Caves. It allows the visitor to see the variety of features that exist in such landscapes including those that are above and below ground, helping to explain the complex environment in which caves form. It also shows how water moves through the limestone and into the Marble Arch Caves itself and helps people to visualise what they can't possibly see otherwise.

This simple piece of physical communication is one of the most popular features in the visitor centre. Its simple approach to communicating the karst environment and the interplay of groundwater within that conveys a basic message that water flows through rocks. But for the more interested user, it displays sinkholes, dolines, cave passages, springs, and a host of other karst features. By linking this with the boat tour through the Marble Arch Caves it connects visitors with the surrounding landscape and makes it instantly relatable.

ii) 100 Great Geosites Initiative

As part of Earth Science Week 2014, the Geological Society of London launched its 100 Great Geosites initiative, recognising the vast geodiversity across Ireland and the UK. One of those sites chosen in the landscape category was Loughareema, in Co. Antrim, also known as the 'vanishing lake'.

Loughareema is an ephemeral lake, hence the name, and it captures the imagination of many because of this quality as it can be completely absent on one visit, and full of water the next. However, its popularity was previously limited to geologists and geographers, and those that lived locally.

The 100 Great Geosites Initiative changed that with the publication of an online resource that explained all of the sites, their locations, and how they formed. Written for a popular audience, the entry for Loughareema brought in elements of the hydrogeology, and also explained the enigmatic quality of the site due to a lack of scientific research at the time.

All of the sites in Northern Ireland were promoted to the local media, and the one that received the most attention was Loughareema. The previously unheard-of site combined with its vanishing nature and the puzzling nature of its formation all provided a story, and one that was still unfolding as research at the site continued. It led to a number of BBC online articles about the site and most recently, a feature on the BBC's The One Show that attracts a daily audience of 5 million people.

iii) NI Science Festival Dye Tracing Event

Arguably one of the most effective ways of delivering geoscience communication is through experiential communication. By physically bringing a story to life, and getting the public involved, it will help to leave those key pieces of knowledge with the audience.

One such event has been run by the Marble Arch Caves in conjunction with the Geological Survey of Northern Ireland as part of the Northern Ireland Science Festival over the past number of years. Dynamic Dye Tracing at the Marble Arch Caves allows families to see first hand how hydrogeologists use dye to trace the flow of water underground.

Participants have the opportunity to see the whole process from start to finish and get a thorough understanding of what the process is, how it works and why it is carried out. This highly visual activity conveys a really simple message, and by active participation, attendees will learn by doing and are much more likely to take home an understanding of dye tracing.

In this case, this experiential communication is very much making the invisible visible, both physically and through the telling the story of the flow of the water from its sink on Cuilcagh Mountain, through the Marble Arch Caves, until its resurgence in the Cladagh Glen.

CONCLUSION

Groundwater has a lot to offer geoscience communication and if done well, can help to bring about a real change in the way that the general public regard geoscience as a subject. However, it needs to be given careful consideration including the type of communication, the audience and key messages, if it is to truly make a difference.

There are many examples of groundwater creating 'light bulb moments' for the public as they realise that rocks have a purpose, and more importantly, one that they can relate to on a daily basis. By sharing examples of these and demonstrating good practice in this area, groundwater can be used as a hook for more and more people to explore the benefits of geoscience.

MAKING THE INVISIBLE HEARD

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ABSTRACT

Informal science learning has been shown to increase interest in and understanding of formal science disciplines. Creative science communication efforts through collaboration with the arts and cultural performances are an effective tool in reaching new and under-engaged science audiences to increase science capital. An immersive science communication experience, "Inception Horizon", is presented here as a case study in creative engagement with groundwater and karst systems through the medium of song and performance, with results indicating the effectiveness of the informal learning approach taken.

Key words: *groundwater, climate change, public engagement, science communication, arts, visual arts, music, informal education.*

INTRODUCTION

Given that groundwater is largely unobservable to the naked eye, people's conceptions of groundwater and other underground resources are typically naive (Dickerson and Dawkins, 2004; Lacchia et al., 2020). In the absence of visible cues, spatial reasoning plays an important role in the development of people's understanding and conceptions of groundwater when constructing mental models of groundwater environments (Dickerson and Dawkins, 2004). Educational engagement initiatives on specific issues of scientific literacy for identified audiences have been shown to lead to effective shifts along the stages in a Theory of Change, from knowledge to intended behaviour, leading to an increase in attitudes supporting sustainable actions (Ashley et al., 2019).

Public engagement with climate science, natural resources and the changing earth system defies a "one size fits all" approach, as the cognitive strategies that influence understanding are dependent on personal beliefs, psychological distance of impacts and other norms (Bain et al, 2012; Bostrom et al., 2013). Best practice in engagement with climate change and earth science has found, for example, that people's willingness to partake in actions is dependent on personal experiences, personal meaning, and local risk (Baldwin et al., 2012; Broomell et al., 2015). Experiential engagements of the earth system and climate change science that are focussed on place-attachment and inferring general global trends from a particular (personal) experience, have been shown to increase likelihood of resulting individual action (Scannell et al., 2011). Furthermore, individuals process information according to social schemas that are shaped by cultural and personal context (Baldwin et al. 2012). Accordingly, information needs to be directed to audiences in a way that is reflective of these cultural contexts and preconceptions. Creative forms of science communication such as the inclusion of the arts with traditional STEM subjects, can effectively increase scientific understanding of public audiences (Conner et al., 2017) and can also free researchers from the somewhat rigid communication framework of their discipline, thereby increasing self-confidence in their ability to communicate their work expressively (Woodley et al., 2022)

The Irish Government's Creative Ireland programme (a major funder of the creative sector in Ireland) states that few sectors are in a better position than the creative and cultural sectors to bridge the gaps between what people know and feel about the environment and climate change through the creation of spaces for dialogue, deliberation, and for allowing people to visualise what their future scenarios will look like. Furthermore, artistic imagination of the underground can be used to advance understanding of both underlying geology and current earth system and environmental change (Hawkins et al., 2020).

At iCRAG, the Science Foundation Ireland Research Centre in Applied Geosciences, efforts to communicate the Centre's science in creative and artistic ways across a number of co-created artist-scientist projects have proven to be successful in breaking through barriers in STEM engagement, to enhance understanding of groundwater and applied geoscience research topics, and to capitalise on the emotional and human connection that the arts can provide. The Centre encourages and facilitates creative relationships between artists, academics and researchers and enables new perspectives on current and prospective research to arise through the lens of artistic practice. It is an artist-led model of interdisciplinarity at university and a practice-based programme that supports the development of new artworks through an exchange of knowledge between the artist and iCRAG researchers. Presented here is an approach to raise public awareness of groundwater, through the medium of choral song, accompanied by sculpture, music and visual projection.

METHODS

Beginning in May 2019, members of the Mellow Tonics choir and composer Norah Constance Walsh began collaborating with choir member and hydrogeologist Prof. Laurence Gill from iCRAG at Trinity College Dublin, on creating a musical celebration of subterranean karst cave systems. The choir members were brought to visit Poll Dubh, a cave system beneath Slieve Elva in the Burren, Co. Clare, where they learned about the hydrogeology of the cave system, water flow through the karst system and how the movement of water along the surface of the limestone came to leave distinct markings on the rock surface (Figure 1). Brief choral practices were held underground, both in torchlight and in the dark, to give both the choir and composer a sense of the acoustics of the underground system, and to place themselves in the shoes of the audience who would experience the music in the cavernous surrounds of the Trinity College Museum Building. Members of the choir and the composer visited numerous sites above ground in the Burren, to get a sense of how the landscape is shaped by water, and how much of the water flow in the Burren takes place underground.

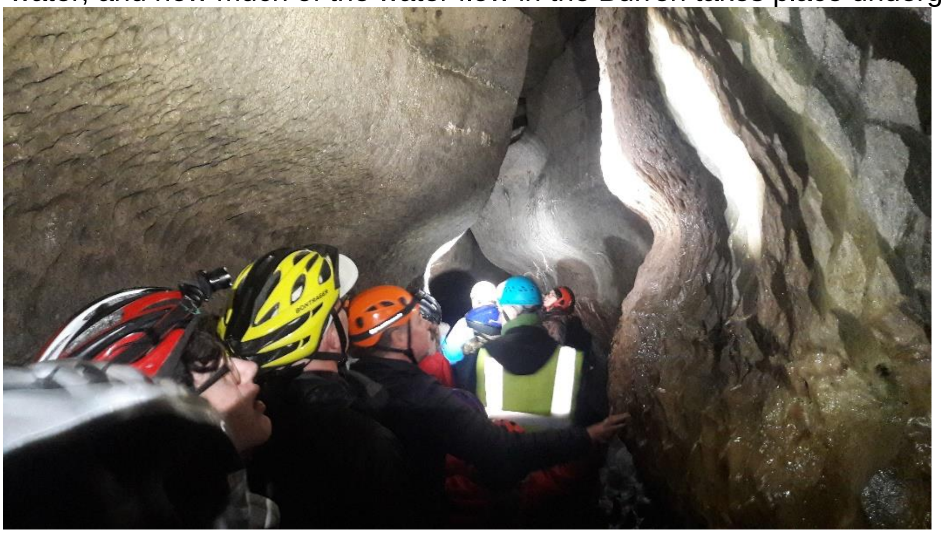


Figure 1: *The Mellow Tonics in Poll Dubh cave in the Burren, Co. Clare.*

Following the field trip, composer Norah Constance Walsh created the *Inception Horizon* choral piece, inspired by adventures at the Devil's Punchbowl, Kinvara, and in Poll Dubh.

Working with the scientific explanations provided by Laurence Gill, the musical work follows the path of *how rain falling on the ground surface, makes its way down through the soil and into the underlying limestone bedrock with its karst passage network"* and into the layers of rock that lie beneath. The musical piece is designed to allow people hear and gain a sense of how groundwater seeps, drips and then gains momentum, as it moves through a cave system, while simultaneously creating and passing through various pathways with its laminar and then increasingly turbulent flow. Over time the groundwater flow carves out a vast cave before finding its way back to the air via a spring.

INCEPTION HORIZON

Inception Horizon
Text: Dr. Laurence Gill. Compiled by Norah Constance Walsh
Music: Norah Constance Walsh

Exposed, weathered down, low-lying
limestone plains
Linked lowland karst network
Ephemeral turloughs
Slieve Elva to Kinvara
Protected unique species, substrate
communities, ecosystem

Excessive precipitation events
Seeping
Insufficient capacity
Surcharge

Inception horizon

First order kinetics, fourth order kinetics
Pathways through the epikarst,
Laminar
D'Arcy's law
Flow through the epikarst
Breakthrough (Inception)
Transition
Turbulence
Linear kinetics
Meteoric waters
Aggressive to calcite
Aggressive, turbulent, meteoric waters

Inception horizon
Extensive dissolution, intensively karstified
Fracture enlargement
Penetrate deeper

Vast, submerged
Far below
Higher order passages
Branching, ramiform, spongework, network,
anastomotic
Vast submerged,
Vast
Deep, deep
Estavelle......spring!

The concept of an inception horizon features strongly in the music of the work. An inception horizon is the crucial weakness in the rock that facilitates the initial passage of water which enables the process of erosion. These initial inception horizons often stretch out like a constant ceiling above the cave passages which form by ongoing descending erosion over thousands of years. In the musical piece, whispers of the corrosive forces at work echo in the space (*"Turbulence, Linear kinetics, Meteoric waters, Aggressive to calcite"*) against an overall trajectory of descent ("*Vast submerged, Far below*"), until the final upwards rush when you can breathe again when the water remerges back out to the atmosphere ("*Estavelle…spring!*"). A sense of local knowledge and lay scientific expertise is derived from mention of the placenames (*"Slieve Elva to Kinvara"*) in close proximity to more technical terminology that is part of everyday vernacular of the local population *("lowland karst", "turloughs", "species" and "substrate communities"*).

Rehearsals by the Mellow Tonics choir took place over a four month period during late 2019 and early 2020, with choir members and composer perfecting the musical nature of the piece, combined with elements of stagecraft (Figure 2).

Figure 2: *The Mellow Tonics with Composer Norah Constance Walsh at the choir final rehearsal before the premiere of "Inception Horizon"*

SHOW TIME

The Museum Building in Trinity College Dublin was selected as the ideal performance venue given the stonework nature of the cavernous interior, and the darkness that could be generated once the lights were turned off, to give a sense of the engulfing darkness in groundwater passages in such underground karst environments. Over 170 audience members attended on the night (Figure 3), which also featured the unveiling of two specially commissioned large, sculpted pieces by sculptor and choir member Helen O'Connell (Figure 4), talks on karst, limestone, caving and groundwater flow from John Walsh (UCD), David Drew, Colin Bunce and Paul Johnston (TCD) and an uilleann pipe performance of "Recharge" composed by Laurence Gill. Working with 7thSense Productions, the interior walls of the Museum Building were filled with luminous projections of caves and turloughs from the Burren area. The event duration was approximately 75 minutes, with the final eight minutes being the premiere of the Inception Horizon choral piece by the Mellow Tonics in the dark, a recording of which can be watched on the iCRAG YouTube channel here. Interviews with composer Norah Constance Walsh, sculptor Helen O'Connell, hydrogeologist and creative lead Prof. Laurence Gill and producer Fergus McAuliffe can be viewed here.

Figure 3: *Composer Norah Constance Walsh addresses the audience*

Figure 4: *Scalloped limestone sculpted by Helen O'Connell*

EVALUATION

Evaluation of audience members and choir members was carried out post-event using: (i) Q&A audio recordings on hand-held mic, (ii) on-camera interviews, (iii) a post-event mixed-methods survey email to all attendees that registered on Eventbrite, and (iv) a mood board positioned on the exit from the building with the prompt phrase *"What does groundwater mean to me"* eliciting written response from attendees.

Evaluation of short- and medium-term outcomes focussed on increasing engagement with the subject area and understanding of karst (n = 19, reported via survey email post-event):

- 89% of attendees indicated that the event increased their understanding of karst
- 78% of attendees indicated that the event increased their understanding of groundwater

The positive response rate is indicative that the event, although not advertised or marketed as a solely scientific event, proved effective in increasing scientific knowledge through the medium of music and art.

Some qualitative findings included:

- *"I had a passing interest in the Burren before this, but now I have a much clearer understanding of how important it is to Ireland's geology".*
- *"[It] opened my senses to the feeling of the karst environment".*
- *"I personally had a background on the concept of karst but I definitely got [a] clear explanation from the event, every word was made easy even to those who haven't seen the formations before."*

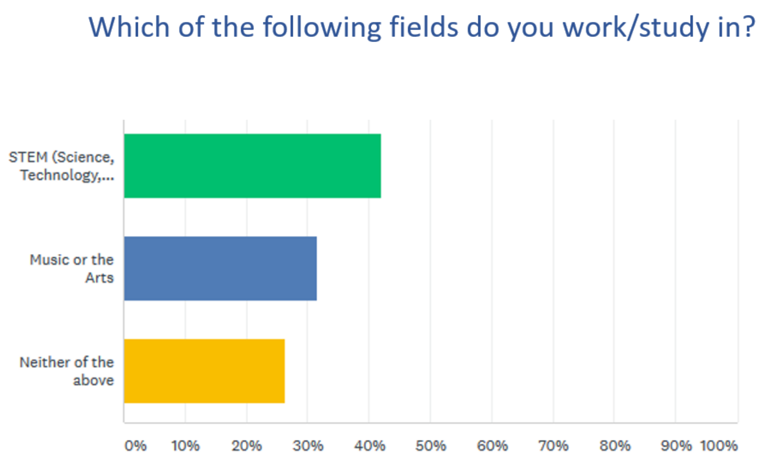
This indicates the level of information provided was done in an accessible and sensory way that aided with increased understanding of this broad topic. Crucially, scientific information was presented in a way that is comfortable to the intended audience, and cognisant of their interests: *"It is really nice to see geology and hydrogeology explained in this type of form".*

Evaluation of long-term outcomes focussed on informed decision making on earth science issues:

• 63% of attendees reported an improvement in confidence about Earth Science issues.

Using a logic modelling approach as part of a wider Theory of Change, the evaluation results can be taken as an indication of increased empowerment in earth sciences, showing that engagement through the arts can be used as an important medium on the pathway towards informed decision making on water resources.

In terms of demographics (Figure 5) the Inception Horizon event was successful in attracting attendees from both STEM (42%) and Arts/Music (32%) backgrounds, with the latter being a key audience for iCRAG due to their high cultural capital, but not necessarily high science capital. The most popular age group was the 45-54 year old age group (42%) followed by 55-64 and 25-34 year old age groups (both 21%). There was a greater representation from those who identified as female (63%) than those who identified as male (32%). Both older audiences and female audiences are key audience for both iCRAG, and the Centre's funder Science Foundation Ireland, due to the increased likelihood of under-engagement with science.



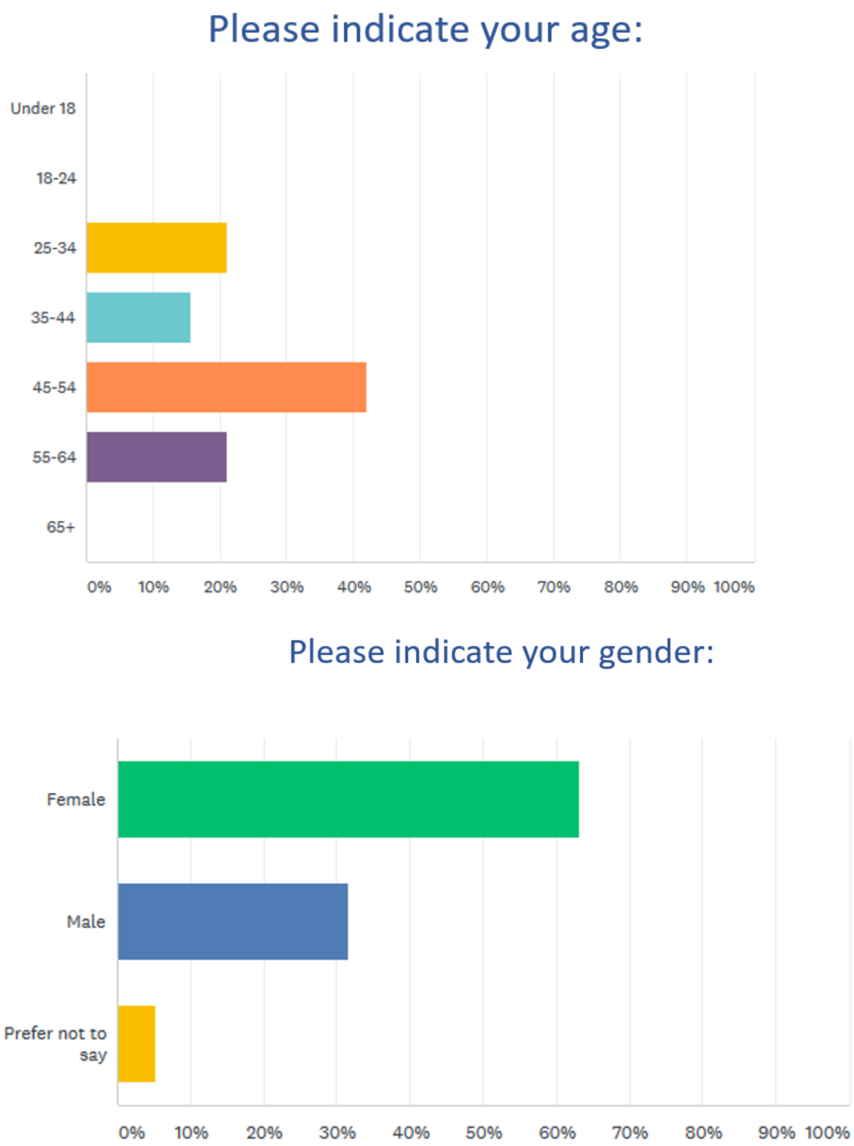


Figure 5: *Post-event evaluation results via response to survey email (n=19). Top: field of employment; Middle: age demographics; Bottom: gender demographics.*

CONCLUSION

The Inception Horizon project is an example of immersive science communication, where the audiences (choir and attendees) is brought into the heart of the subject area, to see, hear, and touch the object of scientific intrigue and research. Similar to James (2017) and Duckett et al. (2021), performative art can be used to successfully reach new audiences that are not necessarily already engaged in science, as borne out by the Inception Horizon evaluation results. Inception Horizon also successfully engaged an older audience in informal science learning which has been shown to deliver enhanced interest in science (Brookfield et al., 2016) and will contribute to an increase in science capital in Ireland.

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EVOLVING COMMUNITY ENGAGEMENT

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ABSTRACT

The Local Authority Waters Programme (LAWPRO) was established in February 2016 following European Commission criticisms of the water governance in Ireland and a lack of public participation during the first-cycle River Basin Management Plan (RMBP), 2009-2015.

Since then, LAWPRO has been coordinating the implementation of the second RBMP (2018-2021) on behalf of the 31 local authorities, by supporting national, regional, and local actions, raising awareness and investigating water quality issues, engaging and empowering communities, and promoting community and stakeholder water stewardship.

Local community engagement is a cornerstone of LAWPRO's work and the Communities Team through funding, resources and supports is helping foster and enable active community groups with the knowledge, skills, and capacity to raise awareness and take-action on local water quality challenges.

INTRODUCTION

LAWPRO, formerly known the *'Local Authorities Waters and Communities Office', is* a local authority shared service, and embraces a new way of working for local government through regional structures but with a local 'bottom up' approach to its core work on the ground. The criticisms of the first cycle RBMP (2009-2015) to meaningfully achieve public participation in local water management and with further statutory obligations placed on the Local Authority sector for implementation of the EU Water Framework Directive (WFD) in Ireland, led to LAWPRO being established.

LAWPRO's work is framed by the WFD which aims to protect and restore healthy water in our rivers, lakes, groundwater, estuaries and coastal waters for the benefit of people, nature and the economy. Public Participation is a key element of the WFD and is set out in Article 14, which states '*Member States shall encourage the active involvement of all interested parties in the implementation of this Directive, in particular in the production, review and updating of the river basin management plans';* thus, one of LAWPRO's core objectives is to develop state agency, stakeholder and community engagement in water quality management under the RBMP for Ireland.

At a regional level this includes formal engagement with the state agencies via Regional Management Committees (RMC's) and Regional Operation Committees (ROC's) and at a local level this entails engagement, support and collaboration with local community groups.

COMMUNITY ENGAGEMENT

LAWPRO's community engagement approach is primarily the responsibility of the 13 Community Water Officer's (CWO) who proactively engage local groups interested in protecting or enhancing their local water environment. This is undertaken by two main strategies: by promoting water quality awareness and by supporting and collaborating on water quality actions.

A targeted approach by CWO's for raising awareness on water quality is to directly communicate with local groups, however there are a variety of engagement methods employed. These include attending local group meetings, correspondence via Public

Participation Networks (PPN), organising water quality related webinars, conferences and publishments, targeting annual and local events, relevant public meetings and shows, community information meetings for PAAs, and leading out on River Basin Management Plan (RBMP) public consultations. These practices ultimately aim to build awareness and understanding of the benefits of healthy waters.

Collaborating with local communities on water quality actions can involve liaison between the relative agencies and stakeholders, and others in the local community on the specific water quality challenges, supplying information, advice and data from LAWPRO's Catchment Scientists and/ or providing administration support and guidance to projects.

COMMUNITY WATER DEVELOPMENT FUND

A significant body of the work of LAWPRO is delivered through the Community Water Development Fund (CWDF). The fund was first introduced through LAWPRO in 2018 following a business case to the Department of Housing, Planning, and Local Government.

The main aims of the fund are to activate public participation in delivering RBMP objectives, support the delivery of measures identified in Programme of Measures set out in the RBMP, build community capacity at a local level, mobilise community action in water stewardship, raise awareness about water, biodiversity and climate change and to support groups and individuals to get involved in citizen science.

The CWDF is delivered through four mechanisms:

1. The CWDF Annual 'Open Call';
2. Projects/studies identified by LAWPRO staff with an element of innovation;
3. A Local Awareness Fund to help CWOs build capacity locally; and
4. Administration of operational costs to Rivers Trusts/Catchment Associations.

The CWDF Annual Open Call makes up the vast majority of the CWDF and invites applications from community groups that demonstrate direct water quality actions and/or water quality awareness benefits. CWOs seek proposals from local community groups in their local authority area(s) and work with each planned applicant giving advice and guidance to ensure proposed projects align with the overarching aims and objectives of the fund.

***Table 1**: CWDF successful groups by category 2018-2021* (RPS, 2021)

Organisation/Groups	No. of projects Awarded			
	2018	2019	2020	2021
Tidy Towns	18	27	33	38
Environment/Biodiversity/Heritage/Tourist Group	15	16	26	20
Development /Residents Association	17	21	19	39
Social Enterprise/Company with no share capital	5	19	13	9
River Trust/Catchment Association	3	10	14	13
Angling Club/ Association	7	10	8	13
Other	4	2	3	17
Festival/Event Group	0	0	2	3
Total	69	105	118	155

Since 2018, applications and funding sought through the open call has grown substantially since its inception (Table 1). From 2018 – 2021 there were a total of 447 grants awarded with almost €1m awarded to date with over €3m sought in grant aid. The process has evolved into a mainly online platform application process.

The application process for 2022 closed in March and evaluation is currently ongoing; there are 202 applications with proposed project costs of almost €1.8m. The budget for 2022 has increased from €380,000 in 2021 to €500,000 for 2022. There is also an additional €10,000 for projects in Blue Dot Areas where grants up to 100% may be awarded. Figure 1 shows grants awarded in 2021 across Rep. of Ireland and Table 2 shows selected community actions to improve water quality.

Figure 1: *CWDF 2021 Map of grants awarded*

Table 2: *Selected community actions for interventions to improve water quality (*RPS, 2021)

Education / awareness	**Physical interventions**	**Partnership / Collaboration**
Produced leaflets/flyers	Fencing	Community groups
Project coverage in local newspaper/radio	Drainage	Landowners
Erected project-related physical signs & notices	Habitat/Biodiversity enhancement	Local authority
Held public workshops/information events/project tours	Barrier removal	State agencies (e.g., EPA)
Group received water quality/biodiversity related training	Nature based solutions to slow flow	Funding organisations
Organised biodiversity event(s)	Tree planting/Landscaping	Other groups (e.g., Group Water Scheme)
Applied for Waters & Communities Special Awards		

WATER AS A HERITAGE

Heritage Week and Water Heritage Day has become an intrinsic part of the LAWPRO calendar since first engaging with the Heritage Council in 2017. This targeted approach invites people locally and nationally, to celebrate our relationship with water, brings a national focus on water and reinforces the message that *'water is not a commercial product like any other but is a heritage that needs protection' (WFD, 2000)*.

CWOs proactively encourage and help organise events with community groups around the country so they can get involved in celebrating their water heritage and explore our connection with water.

Figure 2: *Water Heritage Day Event, Inch River, Co. Wexford, 2021 (Photo: D.O'Keeffe)*

Since 2017 LAWPRO has worked with the Heritage Council in promoting Water Heritage Day events and there have been over 260 events to date. LAWPRO became an official supporting partner for Heritage Week and award sponsor for Water Heritage in 2021. Figure 2 shows such an event last year and Table 3 below shows the growing number of Water Heritage events by year (2017 – 2021).

Table 3: *Water Heritage events by year (2017 – 2021).*

Year	Heritage Week Theme/Message	No. of events
2017	It's in Your Nature	45
2018	Share A Story, Make A Connection	42
2019	Pastimes|Past Times	60
2020	Heritage and Education: Learning from our Heritage	42
2021	Open the door to Heritage	73

Another successful water heritage initiative was the delivered of '*Stories from the Waterside'*, a national story writing competition run during May 2020 to gather peoples' memories and reflections of time spent close to a local river, lake, wetland or the coast. Almost 500 stories were submitted from across the entire island of Ireland, in both English and Irish languages and even further afield from Irish diaspora. LAWPRO published those winners and a further 18 stories in the stories from the waterside book, and also created a website populated by all the stories submitted. There has also been two successful national story reading events held online from the initiative on 'World Wetlands Day' in February 2021 and 'World Water Day' in March 2022. This initiative was delivered in collaboration with The Heritage Council, The Heritage Officers Programme, Inland Fisheries Ireland, and Waterways Ireland.

EVOLVING PUBLIC CONSULTATION

LAWPRO has now taken the lead in two national public consultations for the second (2017) and third RBMPs (2021/2022). The former involved CWOs organising face-to-face public meetings at a local authority municipal district level. This proved hugely successful is getting a high level of submissions for the draft RBMP (2018-2021).

Unfortunately, public meetings for consultation could not be facilitated for the 3rd cycle draft RBMP public consultation due to the Covid-19 Pandemic. Thus, LAWPRO needed evolve and change its approach in order to raise awareness on water quality challenges going forward into the third RBMP cycle (2022-2027); this was essential to get vital public input and submissions to strengthen and critique the draft RBMP.

This was undertaken with online public meetings aimed at local catchment level and via PPNs. Additionally, the online delivery of information was enhanced through the development of an online virtual consultation room via LAWPRO's website which provided explanatory videos, RBMP summaries and an online submissions portal.

Public meetings were advertised via social media (both organic and targeted paid advertising), local and national radio and newspaper, correspondence by CWOs to their local contacts and through local authority platforms.

This combined approach resulted in high awareness of the public consultation meetings resulting in significant number of registrations (Registrants =3060) and excellent attendance rates averaging No. 19 per meeting for the 93 online public meetings, totalling 1179 attendees.

DISCUSSION

The CWDF is strengthening engagement with local communities in relation to our natural waters and is helping to facilitate behavioural and attitudinal change in relation to the management of water resources. A survey carried out by the Economic and Social Research Institute in Jan 2022 (Osawe, & Curtis, 2022) shows evidence that CWDF funding is associated with better public engagement on water management issues. The survey also finds that higher levels of CWDF funding, or repeat grants, are associated with either a higher likelihood of engagement with public and private sector stakeholders, or participation in the river basin management planning process.

Raising awareness of people by providing more information is a commonly utilised behavioural change intervention based on well-established psychological theories such as information- or knowledge- deficit model. LAWPRO see this approach as vitally important to addressing the public participation water literacy challenge across Ireland. It is a vital step in order to mobilise community action on locally water quality challenges and increase public participation in development of Integrated Catchment Management Plans into the future.

LAWPRO's proactive community engagement from CWOs and catchments scientists has sought to raise capacity and look to enable local communities who wish to improve their local water environment. Success to date is borne out in the growing number of groups who are attending and organising meetings and events, and undertaking projects that are focused on caring for their local water environment.

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SESSION IV

FROM SURFACE WATER TO GROUND WATER: MAKING THE INVISIBLE VISIBLE

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ABSTRACT

Nearly half of the Ireland is underlain by limestone that has been karstified in most regions. Karst underground systems transport water primarily through cracks or conduits. Locating the flowing conduits and pathways in karst is important in terms of water resource management, groundwater flooding, geotechnical and engineering projects. Understanding flow pathways is particularly important for road and railway construction, so as not to adversely affect hydrological networks, in particular those associated with Turloughs. The aim of this study is to develop methods for directly detecting energetic ground water flow in sub-surface conduits through passive seismic applications, by detecting the small ground vibrations (seismic microtremor) that flowing water in the sub-surface may generate. This is in contrast to the current 'traditional' approach of attempting to actively image the conduits using geophysical and other methods, in order to determine the geometry of flow paths. Imagery of conduits in karst is a very difficult problem and determining if they contain flowing structures is also a very significant challenge using traditional methods, which is the motivation for developing a new approach to the problem.

INTRODUCTION

Karst is a landscape with distinctive hydrology and landforms that arise when the underlying rock is soluble. Although karst can develop on evaporate rocks such as gypsum and siliceous rocks such as quartzite, the vast majority of karst landforms are found on carbonate rocks, such as limestones. Karst landscapes may have sinkholes, caves, enclosed depressions, disappearing streams, springs and sinkholes. Almost half of the Ireland is underlain by limestone that has been karstified to some extent. Figure 1 shows the geological model representing karst landscape and the distribution of karst features in Ireland. Locating the flowing conduits and pathways in karst is important in terms of water resource management, groundwater flooding, geotechnical and engineering projects and the biological aspects of turloughs.

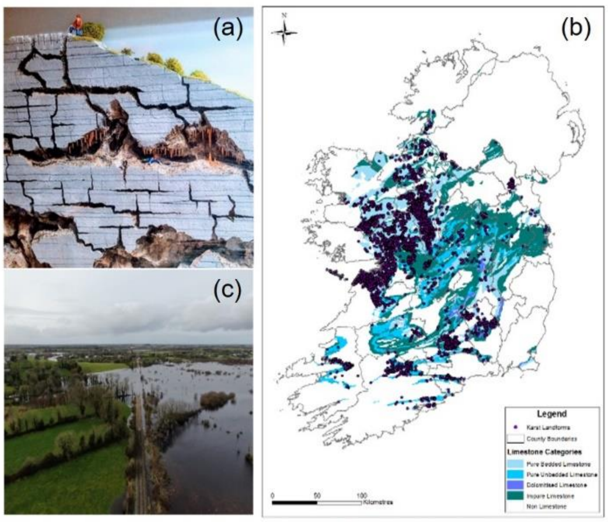

Figure 1. *(a) Geological model of Karst (GSI), (b): distribution of karst features in Ireland (GSI) and (c): an example of groundwater flooding along the western railway corridor near Gort, Co. Galway, in winter 2020 (Galway County Council).*

Karst systems can transport groundwater through a network of conduits and fractures. The current state of the art is that boreholes (wells) are the primary means of determining the location and dynamics of groundwater. However, drilling suffers from relatively poor spatial coverage, is financially expensive and can be logistically challenging. In karst, water flows in subsurface fractures and conduits hence geophysical imagery of these structure (hereafter referred to as *structural imagery*) has been used to infer possible flow paths. Electrical resistivity, ground penetrating radar and seismic methods can all be employed (Hoover & Asce, 2003).

However, karst heterogeneity renders it difficult to image leading to uncertainly in the locations of these structures and whether or not they are in fact 'flowing'. Source to sink dye tests have also been used to define pathway end points (Benischke, 2021), but the intervening flow path is not constrained. In this project, we move beyond the state of the art and focus on directly imaging the source (*source imaging*). The core idea is to use the ground micro-vibrations generated by sub-surface water flow to directly detect the flow (that is, we do not rely on inferring flow, based on a geophysical image (e.g. resistivity) of the subsurface). Although gravity and InSAR can also track spatio-temporal variations caused by subsurface fluids, InSAR spatial scales of ~100m and temporal resolution of 6-12 days (Tribaldos & Ajo-Franklin, 2021) do not compare with the high spatio-temporal sampling potential of seismic signal (~0.2s, < 5m), that can potentially elucidate individual flow structures. Hydrological processes in surface rivers including bed-load transport, turbulent water flow, air bubbles explosion, and propagation of breaking waves induce ground vibrations which can be measured by deploying seismic stations near the river (Figure 2). The clear evidence of the success of fluvial seismology in detecting surface processes motivated us to apply this idea to track and locate the underground flowing conduits in Irish karst by recording the ground vibrations induced by hydraulic processes in karst systems. Since the source of seismic energy is the natural underground water processes, this approach is called passive seismic as opposed to the active seismic surveys where human-made sources such as hammer, airgun, dynamite and vibroseis are used to perturb the medium.

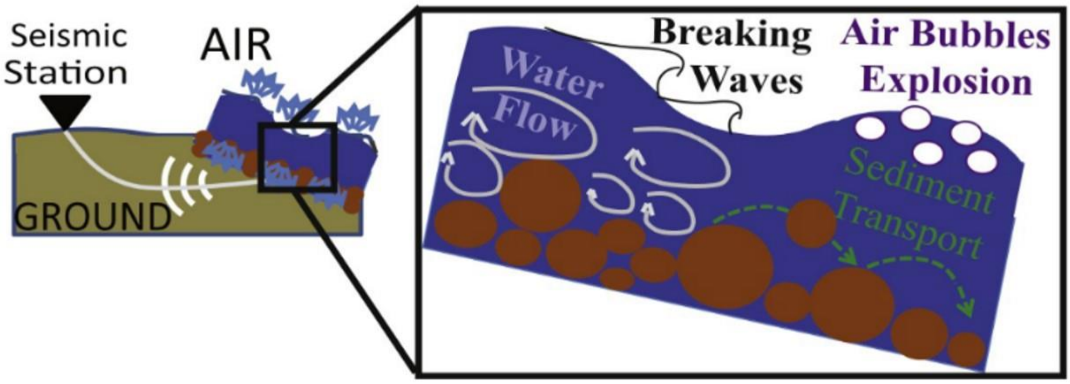

Figure 2. *Schematic representation of induced ground vibrations due to different hydraulic processes in a surface river (Larose et al., 2015). We can record and listen to these tiny vibrations by deploying sensitive seismic instruments around the river.*

GEOLOGICAL SETTING

To test our approach, we conducted two passive seismic surveys on karst sites where the conduits have been previously dived to ground truth our findings. Figure 3 depicts the shapefiles of the conduits at these two sites which have been provided by Geological Survey Ireland (GSI). The first site is at French Park, Co. Roscommon, where the conduit is a shallow simple gently sloping source to sink, within 5m of the surface. We deployed linear profiles consisting of 1Hz short-period seismometers with 2m station spacing. Each profile was deployed perpendicular to the known orientation of an underground conduit. The profile is then moved forward to record the next line until we covered an areal extent of 50*50 m^2. Alternate profiles were deployed for two hours during the day and overnight, respectively. The first five linear profiles consisted of 25 stations with 4m line spacing while the last four profiles consisted of 20 stations with 8m line spacing (Figure 4). After successful application of our method, we conducted another experiment on Polltoophill-Polldeelin Cave, Gort, Co.

Galway, where the conduit is on average 40m below the surface with steep segments at both entrance and resurgence points.

Figure 3. *(a) Pollnagran Cave, French Park, Co. Roscommon, and (b) Polltoophill-Polldeelin Cave, Gort, Co. Galway, Ireland. The shape-file of the dived caves is provided by Geological Survey Ireland (GSI).*

We deployed several monitoring broadband and short-period seismometers in November 2020 along the conduit. Our monitoring seismic stations showed the emergence of the flow signal in March 2021. To test the applicability of the method for a deep conduit and to see geophones are sensitive enough for future applications, we deployed few linear profiles of 5Hz Smartsolo nodes and included a few 1Hz short-period seismometers (to have a basis for comparison) perpendicular to the conduit with 10m station spacing at 4 locations recording between 29-30 March 2021. We also deployed two seismic arrays and undertook an airgun experiment at the Polldeelin Rising (Figure 4). Here, we show the source location applied to the profile near the Polltoophill entrance.

Figure 4. *(a) The coverage of the 50*50 m^2 study area using moving linear profiles of 1Hz short-period seismometers, 15-20th Dec. 2020, Pollnagran Cave, French Park, Co. Roscommon. (b) Seismic experiment between 29-30th March 2021, Polltoophill-Polldeelin Cave, Gort, Co. Galway. For this experiment, we deployed several linear profiles to passively locate the conduit based on the Amplitude Location Method (ALM) as well as two seismic arrays each consisting of 7 stations to track the propagating wavefront generated by the Airgun shots at the Polldeelin Rising. It should be noted that here, because of the scale of the experiment, we mainly use 5Hz geophones, which are easier to deploy but less sensitive than the 1Hz seismometers used in the Roscommon experiment.*

METHODOLOGY

The continuous passive seismic data pre-processing steps consist of removing the linear trend from data, applying a taper and correcting for the instrument response. We computed the spectrogram of the vertical component of the ground motion using sliding windows of 8 second with 90% overlap. The flow-related signal appears as persistent frequency bands between 10-20 Hz which varies with time and station location (Figure 5).

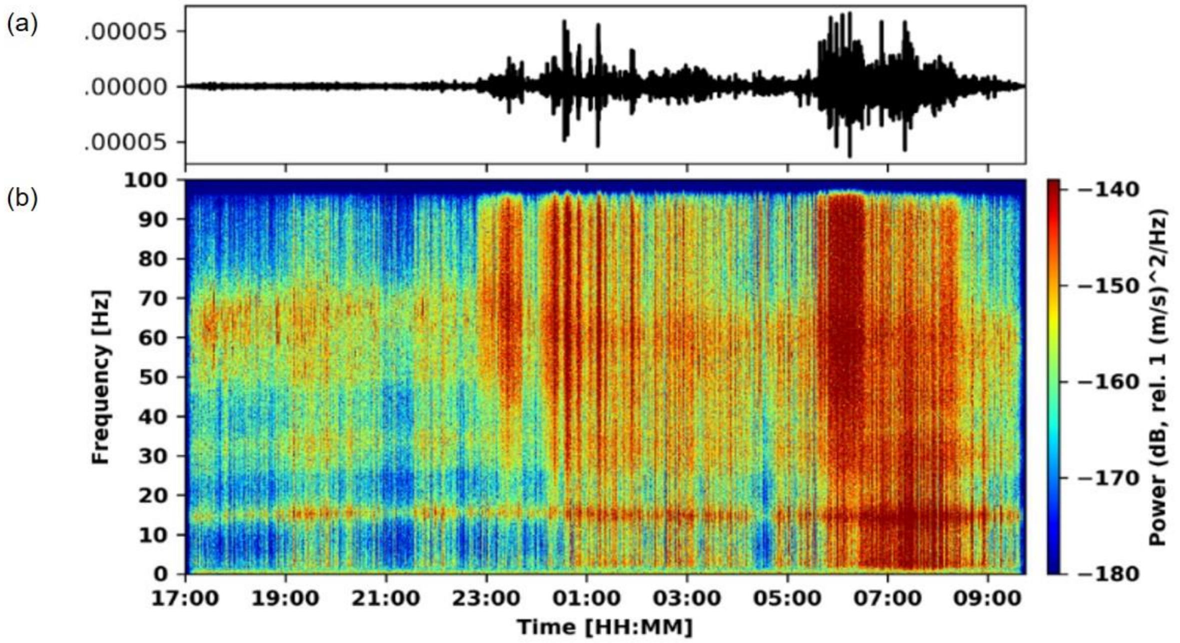

Figure 5. *(a) The seismic trace and (b) spectrogram of one of the stations in the first linear profile. The flow-related microtremor appears as a persistent bandwidth between 10- 20 Hz. As the site was close to a busy road, data contaminated by cultural noise appear as vertical spikes in the spectrogram. Rain and wind also induce ground vibrations in the higher frequency range as can be seen between 06:00 -08:45 A.M.*

Since the flow-related micro-tremor signal has no distinct P- and/or S-arrivals, we use a method based on seismic amplitudes for locating the signal (Taisne *et al*., 2011; De Barros *et al*., 2013). We computed the envelope of the band-pass filtered signal at each station using the Hilbert Transform. Since the sites are close to busy roads, to eliminate the effect of transients mainly associated with cultural noise, we further smoothed the envelope using a moving median filter. The seismic intensity recorded at each station i, with r_i being the distance to the source and I_0 the source intensity is derived using a simple attenuation model as follows where n can be 0.5 and 1 for surface and body waves, respectively. Here we consider surface wave formulation:

$$I_i = I_0 \; e^{-Br_i} / r_i^n$$

where B is computed based on frequency f, quality factor Q and shear wave velocity β as follows:

$$\boldsymbol{B = \pi f / QB}$$

To avoid estimating the source intensity I_0, the intensity ratio between different stations is calculated at each time t:

$$\left. I_i \middle/ I_j \right.^{t} = \left(r_j / r_i \right)^{t} e^{\left[-B\left(r_i^t - r_j^t\right)\right]}$$

The source locations are found through least-square minimization of the misfit between the ratio of the median filtered envelopes between each station pair in the linear profile and the theoretical intensity ratio by considering each grid location as a hypothetical source location. The source locations after applying this method to each individual profile in the first site is shown in Figure 6. The colour-map is reversed to show the minimized misfit map as the most probable source location. To be able to plot all the misfit maps calculated for different profiles, we divided the rescaled misfit maps by the maximum of the colour-map axis. As shown in Figure 6, there seems to be two underground flow paths; one along the main (dived) conduit and the other to the NW end of lines.

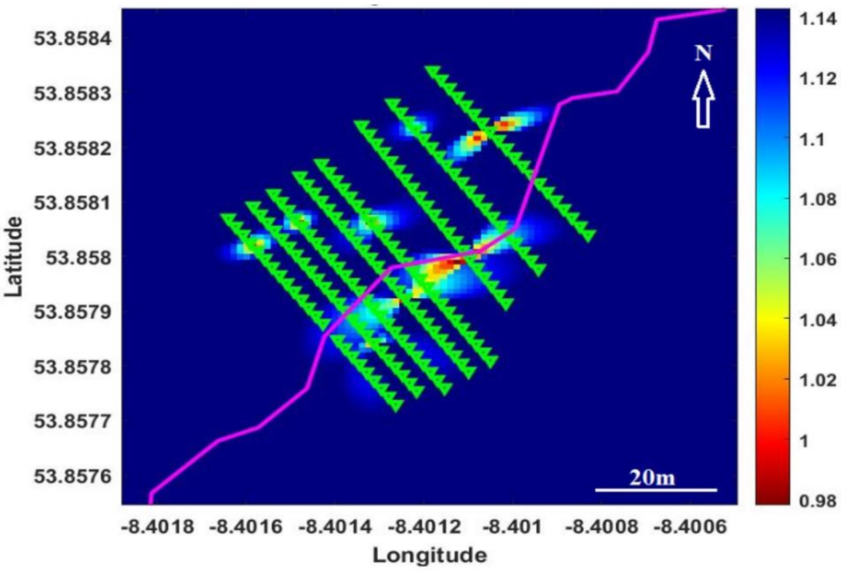

Figure 6. *Re-scaled misfit maps depict the seismic source locations. The colour-map is reversed as the potential source location corresponds to the minimum of the misfit map. There seems to be two underground flow paths; one along the main conduit and the other towards the NW end of seismic profiles.*

Figure 7 shows the results of locating the flowing conduit on the linear crossline profile near the Polltoophill sink. The station spacing is 10m. The spectrogram of one of the stations in this profile is also depicted. The persistent signal around 30 Hz is considered as the flow-related signal. To investigate if this signal has a subterranean flow origin, we applied the Amplitude Location Method (ALM) to this profile. The misfit map locates the source of the tremor where the conduit plunges to depth (Figure 6).

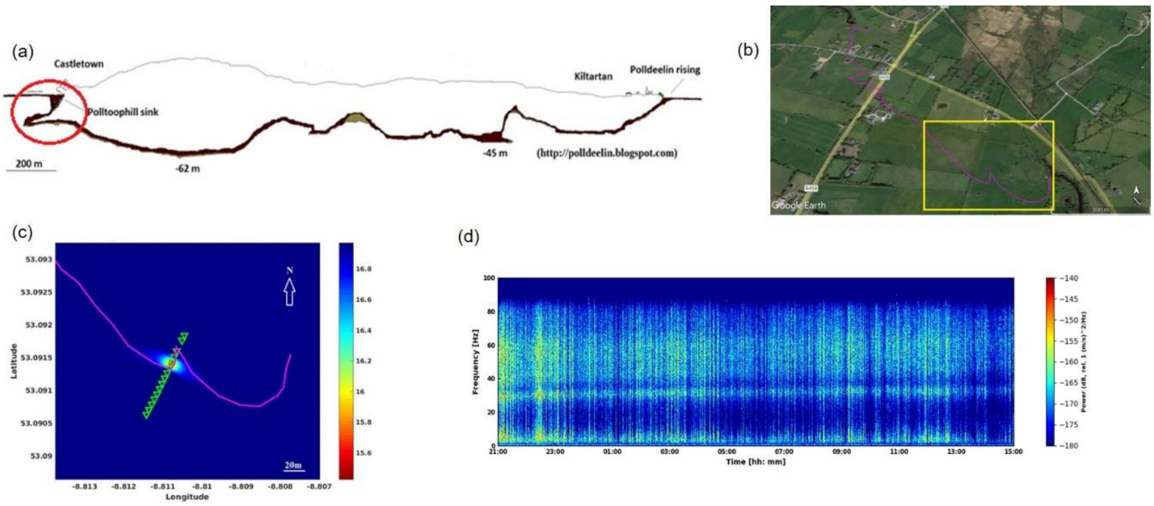

Figure 7. *(a) The misfit map depicts where the conduit plunges to depth, circled on the cross-section, as the source of the persistent signal in the frequency range 30-40 Hz. (b) The yellow box in the middle map shows the extent of the conduit used in the grid search to compute the misfit map (c) in the Amplitude Location Method (ALM). The spectrogram of station 10, short-period seismometer between 21:00 on March 29th and 15:00 on March 30th is shown in (c). Note the persistent frequency around 30 Hz. We applied the Amplitude Location Method (ALM) in this frequency range to investigate whether this signal is induced by the flowing conduit (note also the spectral content of the '30Hz' is drifting in time, likely related to a change in the flow rate).*

We also applied the ALM method to the crossline3 linear profile to locate the source of this signal. Figure 8 shows the conduit as the source of this signal. It is interesting to note that this signals is well away from the sink or the rising, and may be associated with a 'water fall' within the conduit, that is generating seismic microtremor. Also of note is that this signal is likely generated up to 30m below the Earth's surface, based on evidence from the cave dive cross-section. This gives direct flow-related information on deep conduits. We suggest that this is an important results in terms of the overall project objectives, demonstrating that our approach and methodology is capable of locating deep conduits, during time periods (seasons?) and in locations (subterranean waterfalls?) where they have energetic water flow.

Finally, we deployed two water-loggers at the sink and resurgence of the cave in Gort between November 2020 to March 2021. We will investigate the correlation between the flow-induced tremor and water-level change in the conduit, in follow-on work.

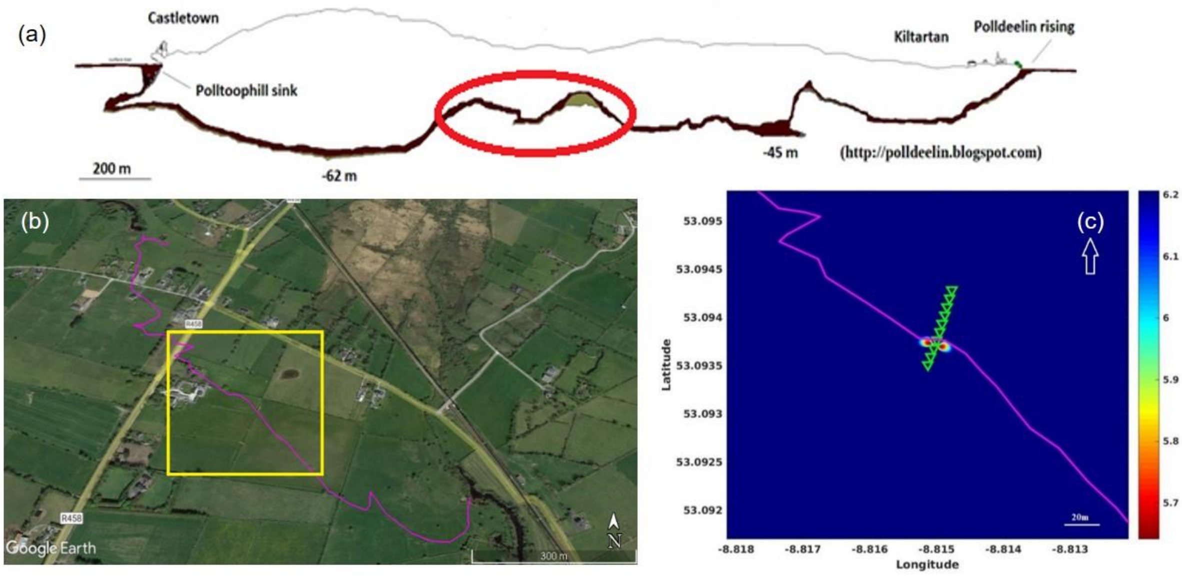

Figure 8. *The misfit map depicts the segment of the conduit that is well away from the sink or the rising, and may be associated with a 'water fall' within the conduit, circled on the cross-section, as the source of the persistent signal. The yellow box in (b) shows the extent of the conduit used in the grid search to compute the misfit map (c) in the Amplitude Location Method (ALM).*

CONCLUSION

We undertook experiments at two sites on karst: Pollnagran Cave in Frenchpark, Co. Roscommon as an example of a gently-sloping shallow conduit and Polltoophill-Polldeelin Cave in Gort, Co. Galway, as an example of a relatively deep and complex-structured conduit. We chose these sites as the caves had previously been dived and we had access to the shapefiles of these caves to ground-truth our findings. We observed that subterranean flow-related micro-tremor in karst appears as persistent frequency bands on the spectrograms that varies with time and seismic station location with respect to the conduit. This persistent frequency is different than the soil resonating frequency and relates to the subterranean water flow in the conduits. Application of an Amplitude Location Method (ALM) to the linear profiles clearly delineated the conduit as the source of the micro-tremor, in both Frenchpark and Gort. We also discovered a secondary (previously unknown) tributary at the Roscommon site which demonstrates that this method has the potential to delineate complex subsurface flow structures. Moreover, the successful application of the method in the second site at Gort suggests that the method may be effective in a wide range of karst scenarios. In this case, we could detect signals associated with water flowing at approximately 30m below the Earth's surface. To date we have not seen this methods reported in international scientific literature.

Acknowledgment

We used the freely available software Obspy (Megies et al., 2011) for pre-processing seismic data and array analysis. We used the code provided by Dr Ka Lok Li (DIAS) for performing amplitude location method. This project is part of iCRAG Geohazard Spoke funded by Science Foundation Ireland (SFI), Geological Survey Ireland (GSI) and Transport Infrastructure Ireland (II). We are grateful to Dr Caoimhe Hickey from the Groundwater program of GSI for providing the maps of potential Karst site locations, fruitful discussions and help with karst site location in Roscommon. We acknowledge Dr Billy O'Keeffe (TII) for help with the problem definition and karst site location. We thank Mr Tony Collins from Galway County Council for his help with site permissioning in Gort. We are appreciative of Mr Ciaran Moran and Mr Paul Cunningham who allowed us to do our experiments in their fields in Roscommon and Gort, respectively. Finally, we thank those DIAS postdocs and staff who helped us with the fieldwork during a difficult situation caused by the COVID-19 pandemic.

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GROUNDWATER CONTAMINANTS OF EMERGING CONCERN

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ABSTRACT

Threats to groundwater quality from contaminants of emerging concern (CECs), a varied and complex mixture of chemical and microbiological and particulate contaminants, are increasingly being recognised as a global issue (e.g. PFAS, pharmaceuticals, microplastic). As such, these threats need to be taken as seriously as historical and regularly monitored contaminants (such as nitrate) if we are to protect groundwater sources, human health and groundwater dependant ecosystems. Research and regulation have gained momentum in the last decade to assess and prioritise key contaminants of emerging concern. However, the evidence-base with which to make sound policy decisions regarding new contaminants of concern is often limited and can take decades to gather. This all too often leads to the situation where monitoring and regulation is adopted far too late in the day and reversing or treating groundwater for CECs becomes hugely challenging and costly. This paper briefly covers the background to some key CECs and how these have been assessed and monitored as part of the recently adopted European voluntary groundwater watch list, an initiative focussed on improving the cycle for CEC prioritisation, monitoring and regulation in groundwater. It then goes on to briefly describe a recent research study focussed on developing a sampling and analytical protocol for microplastics in groundwater and results from the first pilot study of microplastic pollution in groundwater drinking water sources in England.

Key words: *groundwater, contaminants of emerging concern, health, microplastics*

KEY GROUNDWATER CONTAMINANTS OF EMERGING CONCERN

A large variety of trace contaminants are detected in groundwater at potentially environmentally significant concentrations. They are typically referred to as contaminants of emerging concern (CEC) or emerging contaminants (ECs). CECs are a broad group of contaminants and include microbiological contaminants such as viruses, microbial resistant bacteria, anthropogenic particles such as nano-micro plastics and engineered materials and not only newly developed chemicals but also chemicals newly discovered in the environment, in some cases due to analytical developments. Prominent examples include, perfluoroalkyl and polyfluoroalkyl substances (PFAS), organo-phosphorous based fire retardants, polypropylene and polyamide microplastics, pharmaceuticals (e.g. carbamazepine), personal care products (PPCPs), pesticide metabolites/degradation compounds, veterinary products, industrial compounds/by-products, food additives as well as engineered nano-materials.

These types of compounds (largely organic) are used by society in huge quantities for many different purposes including, industrial manufacturing processes, human and animal healthcare, and the production and preservation of food, to list just a few. In the last few decades there has been a growing interest in the occurrence of these CECs in the aquatic environment, their environmental fate and potential toxicity (Kümmerer, 2009; Lapworth et al., 2012). Due to the vast array of possible compounds, many published studies have selected CECs according to priority lists established considering usage, predicted environmental concentrations as well as toxicological, pharmacological and physicochemical data (Hilton et al., 2003). To date the occurrence of CECs has been much better characterised in wastewater and surface water compared to groundwater.

ESTABLISHING A EUROPEAN GROUNDWATER WATCH LIST FOR CEC

There is clearly an urgent need to improve assessments of CECs in groundwater. We can't monitor for every possible CEC, there are simply too many. Furthermore, differences in hydrological processes, contaminant sources and pathways may result in a different range of key CECs relevant for groundwaters compared to surface waters. Groundwater, which is a critical water resource in Europe (and elsewhere globally) and its protection is a priority for the European Commission and European Union (EU) Member States, recent members (such as UK) and associated countries. Current European regulation, both EU regulation, and that of individual nations, only covers a very small fraction of anthropogenic substances that potentially pollute groundwater. Monitoring for other, currently unregulated substances, is very limited or not carried out at all. Therefore, a coordinated European-wide approach was needed to identify, monitor and characterise key priority substances, or groups of substances, that have the potential to both pollute groundwater and also are of potential concern from a health and environmental risk perspective. It is critical to develop an evidence base on these priority CECs for policy development and controls on these currently unregulated substances to be developed in a timely way.

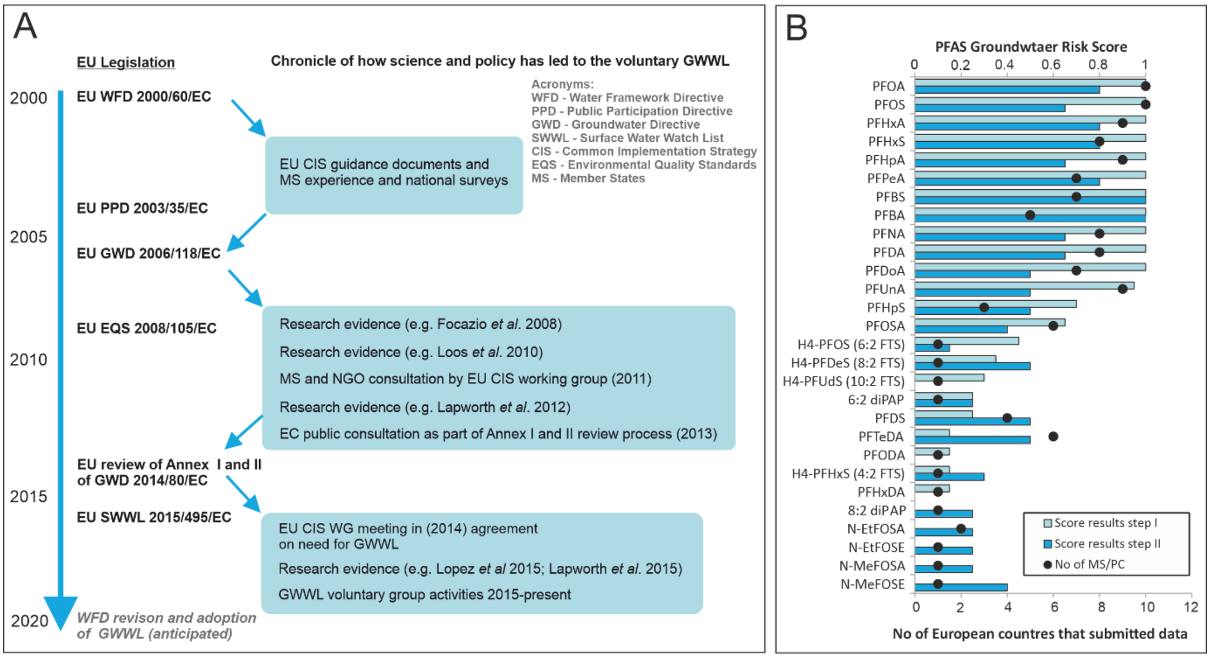

Figure 1: *Development of a GWWL in Europe. A) Chronicle of how research and policy has led to the European voluntary GWWL, B) Groundwater risk scores for selected PFAS compounds monitored in Europe. Source: adapted from Lapworth et al (2019).*

The European Commission highlighted this as a need during the review of the EU Groundwater Directive Annexes in 2014 (Figure 1A), when the requirement to develop a Groundwater Watch List (GWWL) was established (Lapworth et al., 2019). A voluntary initiative as part of the EU CIS Working Group Groundwater was initiated to establish the first voluntary European GWWL. The process for developing the GWWL is one that brought together researchers, regulators, and industry. An initial GWWL was established in 2018 comprising less than 20 priority compounds and this was subsequently revised based on an assessment of the availability of data for key watch list compounds. Figure 1B shows groundwater risk scores developed for PFAS compounds which European countries have collected data for. These risk scores were based on (i) groundwater occurrence and ability to leach to groundwater and (ii) leachability and toxicity combined (Figure 1B). Several PFAS compounds and some pharmaceuticals were included in the original GWWL but are no longer on the list as it was found that sufficient data was already available to pass on to the EU for formal Annex I and II assessments. As such, the GWWL is a dynamic list of priority compounds, which is updated once sufficient monitoring data has been acquired for specific compounds or groups of compounds to enable other high priority compounds to be included. More recent GWWL activities have focussed on pesticide metabolites currently described as 'non-relevant metabolites' which are not routinely considered by European environment agencies and organisations responsible for monitoring the state of the environment (WFD CIS 2021).

RECENT CASE STUDY ON MICROPLASTIC POLLUTION IN GROUNDWATER

There is currently no systematic monitoring of microplasctics (MP) in UK groundwater or in sentinel groundwater ecology (e.g. stygobites), and no documented/standardised protocols that have been field-tested on untreated groundwater sources. A recent study led by the British Geological Survey on behalf of Department of Environment, Food and Rural Affairs and Drinking Water Inspectorate set out to develop a protocol for groundwater and stygobite microplastic (MP) sampling and analysis and undertook a pilot study to test these protocols for assessing MPs in groundwater sources. The results are reported by Lapworth and Shockley (2022) and are briefly summarised below.

A total of 11 groundwater samples from 8 groundwater sources and a method blank were collected, processed and analysed for MP by Fourier Transform Infrared spec. (FTIR). Two stygobite samples and a method blank were also sampled and processed by FTIR. A total of nine MP compositions were analysed for by FTIR. Overall low numbers of MPs were detected in groundwaters, with the highest numbers being detected from pumped sources within the Thames gravels (up to 18 MPs) compared to the pumped chalk (up to 5 MPs). After blank correction, a total of 40 MP particles were found across all samples using FTIR (Figure 2). A single polypropylene (PP) particle was found in the groundwater method blank.

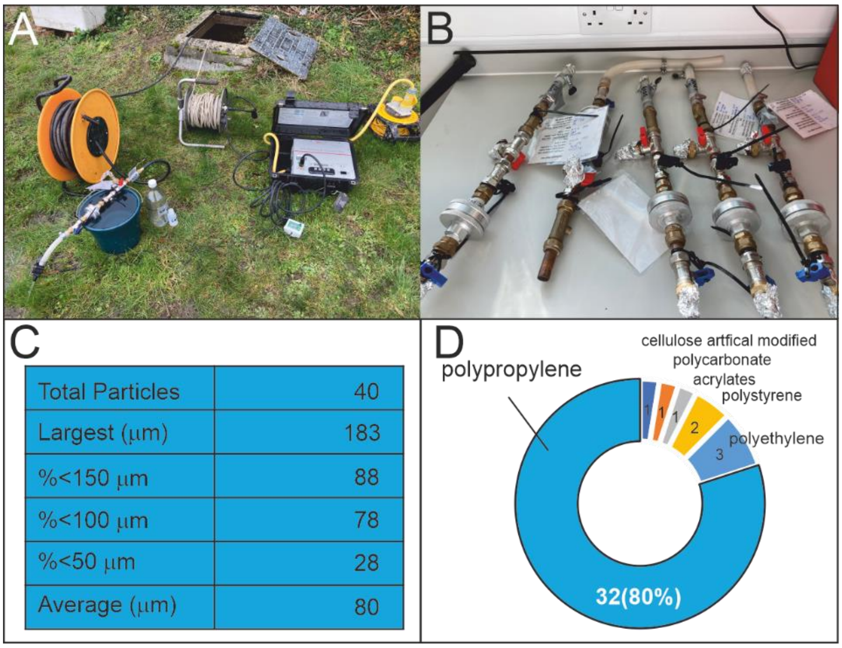

Figure 2: *Developing and testing a protocol for sampling and analysis of MP in groundwater. A) Field testing sample filtration methods, B) In-line filter rigs for isolating MP from groundwater, C) MP size characteristics analysed by FTIR, D) MP composition and number in groundwater samples. Source: adapted from Lapworth and Shockley (2022).*

Overall, a very small proportion of the particles detected by FTIR were microplastics. Of those detected as MPs the largest detected was 183 μm, 28% of particles were <50 μm, 78% <100 μm and 88% <150 μm. PP dominated the polymer composition of MPs found in samples collected from boreholes (80%), four other polymers were also detected including polyethylene (PE - 8%), polystyrene (PS - 5%) and acrylate, polycarbonates and artificial cellulose all ≤ 3% (Figure 2). No MP were detected above the method blank for stygobites samples. Two PP MPs were detected in the stygobite method blank and two PP MPs detected in one of the stygobite samples. The methodologies developed and tested are described in detail in Lapworth and Shockley (2022) and are highly suited to sampling pumped groundwater sources with low turbidity for MPs. Overall, the method was suitable for filtering large groundwaters samples and it was possible to filter up to 100 L in the field from the majority of sources within a relatively short time period (i.e. 1 h), it would therefore be possible to filter 2 or 3 times this volume in the field from many sites based on the small sample used in this pilot study. This pilot study is just a starting point and further refinement of the method is needed and clearly much larger numbers of sites need to be sampled to obtain a representative sample for assessing MP occurrence in groundwater.

SUMMARY AND FUTURE OUTLOOK

Groundwater has a critical role in supplying drinking water and underpinning environmental flows for groundwater dependant ecosystems, but there needs to be more progress towards assessing groundwater quality threats, including by CECs, and protecting groundwater resources and human health. Improved understanding and characterisation of groundwater quality threats are essential for managing groundwater resources and mitigating a range of anthropogenic threats to water supplies globally. This includes the development and use of novel monitoring approaches to improve assessments of groundwater quality. It is essential to continue making progress and prioritise assessments of CECin groundwater which are currently poorly understood but could pose significant health and environmental impacts now and in the future. Initiatives such as the voluntary GWWL are a useful approach to help prioritise efforts and in particular fast-track monitoring for new CECs in the future. Prominent groups of CECs that currently warrant further investigation in groundwater include, but are not limited to, PFAS compounds and organo-phosphorus based fire retardants, pharmaceutical compounds, microplastics, anti-microbial resistant bacteria and viruses.

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WHAT'S THE PFUSS ALL ABOUT? PRAGMATIC PFAS MANAGEMENT OPTIONS.

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ABSTRACT

Per- and Polyfluoroalkyl Substances (PFAS) comprise a group of over 9,250 organofluorine xenobiotics, with significantly accelerating regulatory attention as a result of widespread detection in drinking water above safe levels. The initial regulatory attention was focussed on two individual anionic compounds within this class, perfluorooctane sulphonate (PFOS) and perflurooctanoic acid (PFOA), but in recent years the focus has expanded to include a vast array of additional PFAS. Many of these additional PFAS are termed precursors which transform in the environment via microbial action to form PFOS, PFOA or other PFAS.

PFAS are extremely persistent or transform into persistent 'dead end' daughter products, they generally tend to be water soluble and so are mobile in the environment, some can bioaccumulate and their toxicology is becoming better understood.

PFAS are used in numerous commercial products, however their ongoing use in Class B firefighting foams, especially during fire training, can often lead to significant losses of PFAS to ground, which can then potentially impact drinking water supplies.

The extreme persistence and mobility of PFAS means that they can be detected at low levels in soils, surface waters, rainwater and groundwater globally. With a greater understanding of the toxicology of PFAS, regulatory compliance thresholds are becoming extremely low, meaning that levels considered as "background" concentrations may now be perceived to be toxic or out of compliance.

The focus when considering pragmatic PFAS management must be elimination of potential exposure pathways to sensitive receptors. A significant mass of PFAS can remain associated with soils and pavements where they have been lost to ground. Cationic PFAS are generally retained by soils and PFAS are described to exist in supramolecular forms concentrated at interfaces, which potentially represent significant retardation mechanisms.

INTRODUCTION

Poly- and Perfluoroalkyl substances (PFAS) are used in a wide range of industrial applications and commercial products due to their ability to repel water and oils. As PFAS are extremely persistent and mobile in the environment they are being discovered in drinking water supplies above safe levels in many countries, with a drinking water supply well in Cambridgeshire recently described to have been impacted at four times the UK legal limit of 100 ng/L [1]. A study commissioned by the Irish EPA in 2021 confirmed the presence of PFAS in both surface and groundwaters, at the 5 sites which were selected for assessment [2].

It's clear that the use of all PFAS in commerce will be subject to regulatory scrutiny to determine if alternatives are available or if specific uses are essential.

This article aims to describe the fate and transport of PFAS, discuss analytical tools and treatment options and uncertainties such that PFAS sources and plumes can be effectively managed. It highlights the need to transition away from firefighting foams that contain PFAS and to implement effective decontamination as part of this process.

WHAT ARE PFAS?

PFASs are a very diverse class of xenobiotic “man-made” chemicals, united by the common structural element of a fully fluorinated carbon (alkyl) chain, known as the perfluoroalkyl group which is typically 2 to 18 carbon atoms in length. The whole PFAS molecule may be either fully (per-) or partly (poly-) fluorinated, but each compound always contains a perfluoroalkyl group.

Perfluoroalkyl substances have previously been referred to as perfluorinated compounds (PFCs) but are now more commonly termed perfluoroalkyl acids (PFAAs) and contain a fully fluorinated carbon chain with no additional carbon to hydrogen bonds in the molecule.

Polyfluoroalkyl substances comprise by far the more diverse group of PFASs, as compared to perfluorinated compounds, with thousands of compounds synthesised for a broad array of commercial uses. In addition to the perfluoroalkyl group, polyfluorinated compounds contain carbon to hydrogen bonds, such as fluorotelomers, but also may have more complex functional groups which can be neutral, anionic, cationic or zwitterionic. Polyfluorinated compounds include highly volatile fluorotelomer alcohols (FTOHs), fluorotelomer sulfonic acids (FTSs), polyfluorinated alkyl phosphates (PAPs), perfluorooctane sulfonamides (PFOSA) and many thousands more compounds, which have a very wide range of physical and chemical properties

Polyfluorinated PFASs biotransform in the environment (more rapidly under aerobic conditions) and in higher organisms to create PFAAs and are thus termed PFAA-precursors.

PFASs may also be subdivided into two broad classes, short-chain PFASs and long-chain PFASs, with long chain PFCAs comprising those that have 7 or more perfluoroalkyl carbon atoms (e.g. PFOA) and long chain PFSAs having 6 or more perfluoroalkyl carbon atoms (e.g. perfluorohexane sulfonic acid (PFHxS) and PFOS) [3]. Studies have been conducted that indicate long-chain PFASs have a higher potential to bioconcentrate and bioaccumulate through trophic levels as compared to shorter-chain PFASs [4].

USES

There are many common uses of PFAS in commercial products, but major dispersive uses are often associated with use of Class B fire-fighting foams. Additionally bulk use of PFAS at facilities involved with metal plating, printing, photolithography, rubber, leather or textile manufacturing may also result in loss of PFAS to ground and use in car waxes and for reproofing garments at dry cleaners may be of concern. It’s common to find PFAS associated with landfills which emit PFAS in leachates and wastewater treatment plants which concentrate some PFAS in biosolids, and these sources can also emit volatile PFAS to atmosphere.

PFAS, termed fluorosurfactants are also major components of firefighting foams used to extinguish flammable liquid fires such as aqueous film forming foam (AFFF) and fluoroprotein foams. For this highly dispersive application, advancing regulations are curtailing their use, with alternative fluorine free firefighting (F3) foams demonstrating comparable extinguishment performance using large scale tests [5-7]. There are many uses of PFAS for which non-fluorinated alternatives are available such as in packaging and fabrics.

A study commissioned by the EPA 2022, determined that over 1 million litres of PFAS containing foams were in stock within Ireland at respond sites included within the study, which was determined to be held at a relatively small number of large industrial fuel storage/processing facilities or at large pharmaceutical facilities with solvent/fuel tank farms [8].

REGULATORY CONTEXT

Drinking water standards for PFAS continue to be set at exceptionally low levels in what may be perceived as a “race to the bottom”. The concern being that as compliance levels are set so low, they are at comparable levels to those identified in multiple environmental matrices as “background” detections such as rainwater. The regulatory level for perfluorooctanoic acid (PFOA) in drinking water was recently set at 2 ng/L in Illinois [9] whilst in Denmark a 2 ng/L level has been set for the sum of PFOA, perfluorooctane sulphonic acid (PFOS), perfluorohexanesulphonic acid (PFHxS) and perfluorononanoic acid (PFNA) in drinking water [10].

In the US the EPA recently released a PFAS strategic roadmap [11] which, amongst many other actions requires the EPA to set enforceable drinking water limits for certain PFAS under the Safe Drinking Water Act in the winter of 2022 and by the spring of 2022, draft a proposed rule designating certain PFAS as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Whilst in October 2021 the UK drinking inspectorate instructed water companies to assess every raw drinking water abstraction for some 47 different PFAS [12] following announcement of new lower drinking water standards for PFOS and PFOA (at 100 ng/L) in January 2021 [13]. Meanwhile European regulations on PFAS in drinking water required that the sum of 20 individual PFAS are below a 100 ng/L limit value [14].

CHEMICAL ANALYSES

Analytical methods to assess the presence of the polyfluorinated precursors and PFAAs, such as the total oxidisable precursor (TOP) assay have been commercially available since 2015. This method can detect a wide range of PFAA precursors indirectly, by converting them into PFAAs using a chemical oxidant, so the resulting PFAAs can then be detected, as their chemical analysis is often possible. For the TOP assay to be applied to quantitatively detect PFAA-precursors in soils some additional extraction methods are required which focus on removing cations and zwitterions, so that they can then be quantified. Recent research has shown that 97% of the PFAS in soil sources remain undetected [15]. The TOP assay could be described as the PFAS uncloaking tool, but care needs to be taken ensuring that the published data quality objectives are met [16] and that interpretation is accurate.

FATE & TRANSPORT

As PFAS are highly persistent and mobile in the environment, the common sensitive receptor can be drinking water supplies located some distance from where PFAS have been used. PFAS can also travel from source areas in surface waters which may be eventually used as drinking water supplies, or PFAS can bioaccumulate in fish which may result in secondary poisoning when the fish are consumed.

When assessing PFAS at any location, there are various chemical analytical tools that can be applied which detect differing PFAS. It is very important to confirm that the PFAS detected are associated with a product that may have been used at the site. Also confirming that the concentration of PFAS detected indicates that they could not be present as a result of atmospheric deposition. Developing an understanding of the regional background concentrations can be very important.

The fate of any PFAS discovered generally needs to be assessed by considering migration routes via groundwater and surface waters. Assessment of the site setting and potentially relevant receptors can provide an initial undertraining of the potential for harm from any detected PFAS.

The PFAS present in all fluorinated firefighting foams comprise a mixture of perfluoroalkyl substances such as perfluorooctane sulfonate (PFOS) as well as other polyfluoroalkyl substances, with foams still currently in use being dominated by polyfluoroalkyl substances. The polyfluoroalkyl substances tend to be proprietary molecules which cannot be detected using conventional chemical analyses, but they biotransform in the environment, to create the detectable and regulated perfluoroalkyl substances, such as PFOS, PFOA and shorter chain, more mobile PFAS such as perfluorohexanoic acid (PFHxA). These perfluoroalkyl substances are collectively termed perfluoroalkyl acids (PFAAs) and include PFOS PFOA, PFNA, PFHxS and PFHxA. The polyfluoroalkyl substances have been termed PFAA-precursors as they create PFAAs and the fact that these precursors remain hidden from conventional chemical analyses has lead to them being termed as “Dark Matter”. [17]. A biotransformation funnel showing the generation of PFAAs via common daughter products from a parent PFAA-precursor found in some fluorinated firefighting foams called 6:2 fluoromercaptoalkylamido sulphonate (6:2FTSAS) is shown in Figure 1.

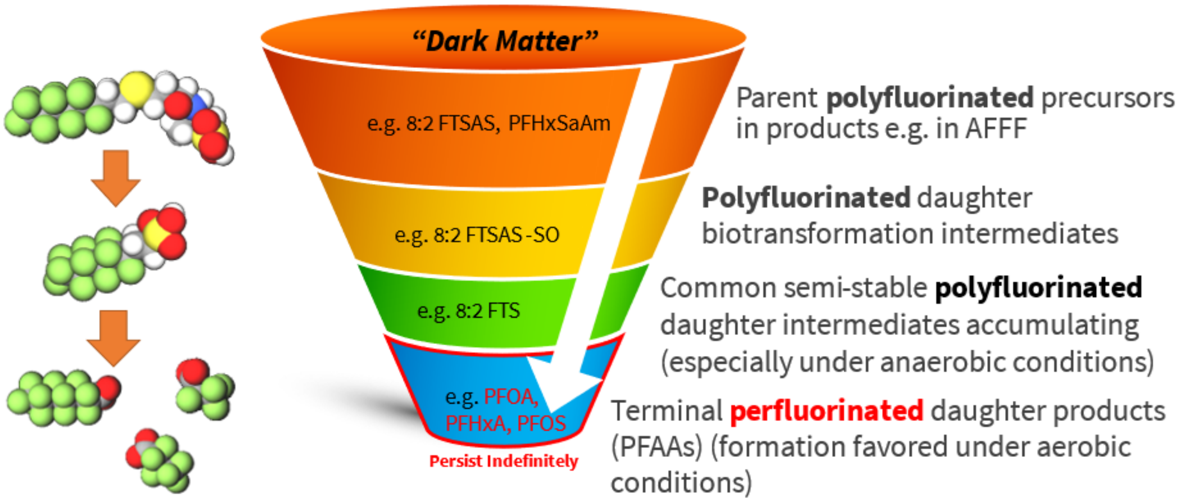

Figure 1: *Environmental Transformation of Polyfluoroalkyl PFAS to Create Persistent PFAAs*

The PFAAs are extremely persistent in the environment, tend to be negatively charged (anionic) thus highly mobile and their mobility increases as the length of the perfluoroalkyl chain decreases, so shorter chains can travel further in groundwater. The polyfluoroalkyl substances can be positively charged (cationic) or have a combination of charges (zwitterionic) meaning they are retained by most soils and aquifers, thus they can remain in locations where firefighting foams have been applied, such as fire training areas. They can then represent an ongoing source of PFAAs, as charge switching can occur as these PFAA-precursors biotransform, meaning they are converted from less mobile cationic and zwitterionic forms to much more mobile anions, such as PFOS, PFOA, PFHxS, PFNA and PFHxA. The further complexity is that amphiphilic PFAS, self-assemble in bilayer structures which can stack into multiple layers, such that multi-layered coatings can be present on surfaces. Amphiphilic PFAS have been shown to concentrate on concrete surfaces which then act as source of PFAAs for decades to come.

PFAS have been shown to be associated with the air water interface, and can also be stored on the surface of groundwater [18]. So, whilst many PFAS are highly mobile and subject to long range transport, there can also be a significant reservoir remaining at the source (e.g. fire training areas), associated with surficial soils, concrete and the capillary fringe (or smear zone) where the water table fluctuates. The presence of high levels of undetectable PFAA-precursors in soils can have significant implications when selecting remedial technologies as the “*Dark Matter*” can mean certain remedial approaches are potentially ineffective unless their performance on the PFAA-precursors is proven. A generic conceptual site model (CSM) describing PFAS fate and transport is presented below in Figure 2. Tetra tech is applying a specialist cleaning agent termed **PFAS**crub® to remove PFAS from soils and this has been demonstrated to remove an order of magnitude more PFAS than using water alone.

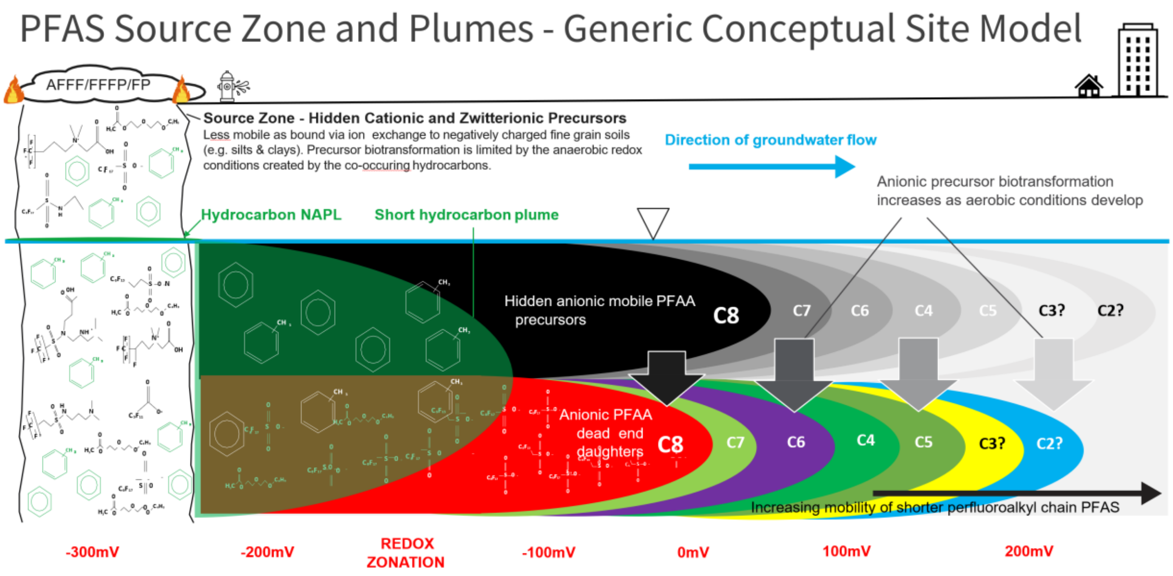

Figure 2: *Generic Conceptual Site Model Considering PFAS Fate and Transport [19].*

PFAS REMEDIATION

When considering treatment of PFAS impacted waters such as groundwater and surface water, characterising the water using TOP assay can be essential to allow design of the treatment solution. Estimation of the capacity of a water strategy may be flawed if only a fraction of the PFAS in the water has been assessed. This can be more important when considering water that is being extracted from an area close to a PFAS source, as there will have been less time for the PFAA-precursors to have been transformed via biological activity.

Activated carbon is more effective for treatment of the longer chain (more hydrophobic) PFAAs such as PFOS and PFOA, as opposed to the shorter chains such as PFHxA. For shorter chain anionic PFAS, ion exchange resins are generally more successful, as electrostatic interactions can be used to remove them from water. Characterising the water that needs treating for natural organic matter and common anions, such as sulphate, can be very important to determine the likelihood of successful treatment. Running small scale column studies and water treatment laboratory scale or field pilots can be used to design treatment systems.

Other technologies that are developing to remove PFAS from water include multiple proprietary sorbent media and foam fractionation, to remove PFAS from solution and concentrate it. Treatment methods that apply oxidants, such as ozofractionation, which applies ozone in foam fractionation, will convert PFAA precursors into PFAAs, meaning that some of the amphiphilic PFAA precursor that could readily be separated by the foam fractionation process are instead oxidised into a short chain PFAAs that are not as easily removed [20]. Application of oxidants, such as ozone, or biological attack on common PFAA-precursors, known as fluorotelomers, leads to the generation of a series of short chain PFAAs, including some termed ultrashort PFAAs (with 1 to 3 carbon atoms in their chain), that are not detected using commercially available analyses. The generation of a third of the mass of precursors as ultrashort chains has been reported when oxidants are applied [21]. Transformation of a fluorosurfactant found in certain aqueous film forming foams (AFFFs), through 6:2FTS (6:2fluorotelomer sulphonate) is shown in Figure 3. This process will occur if oxidants or aerobic biological treatment processes are applied to treat PFAS which often includes PFAA-precursors. So, application of water treatment technologies using aerobic biological processes and chemical oxidants may lead to the formation of more mobile PFAS.

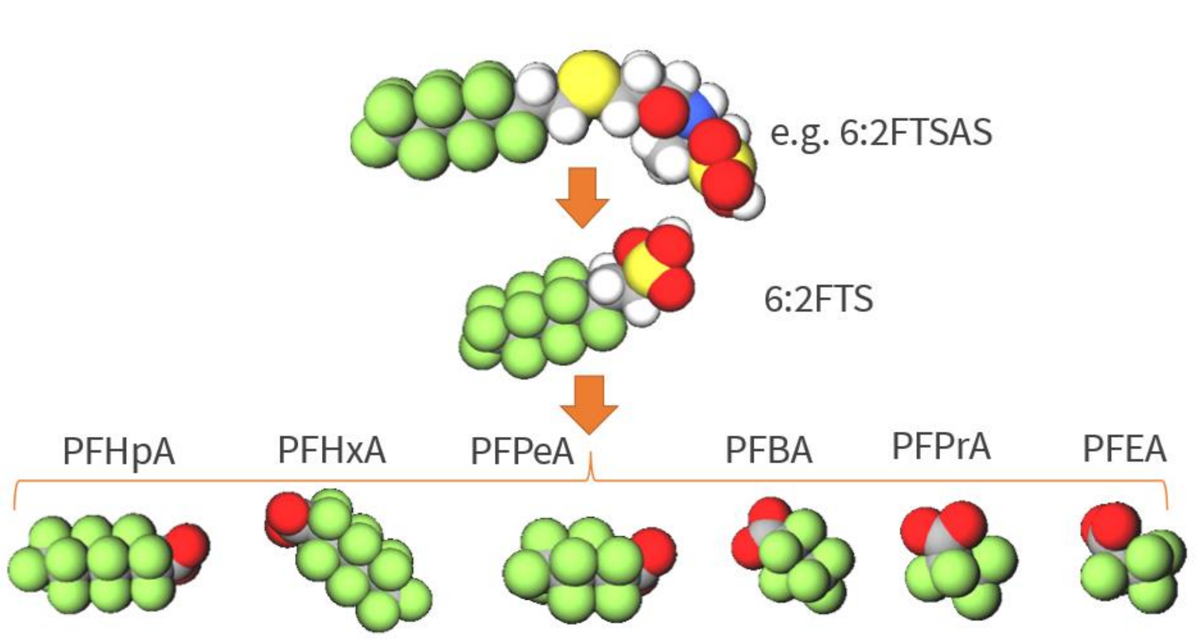

Figure 3: *Conversion of PFAA precursors to a range of PFAAs via chemical oxidation or biotransformation.*

A series of remedial technologies that separate and destroy PFAS are being developed, with Tetra Tech leading the way in scaling up destructive approaches such as sonolysis, electron beams and use of supercritical water oxidation.

SUMMARY

Management of PFAS impacts to ground requires a detailed understanding of the unique behaviours of this class of compounds, where physical, chemical, and biological processes can act to retain or mobilise PFAS from soils into groundwater or surface waters which can impact drinking water supplies. As regulations become increasingly comprehensive and stringent, the risks posed by a wide range of PFAS will need to be considered. When considering remediation of soils impacted by PFAS, there are significant uncertainties characterising PFAS, which is an essential step before embarking on a remedial approach. Tetra Tech can assist with characterising and treating PFAS, as a result of our experience characterising, risk assessing and treating this class of contaminants since 2005.

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IRISH HOLY WELLS: THEIR GROUNDWATER SOURCES, WATER CHEMISTRIES AND HEALING REPUTATIONS

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ABSTRACT

A study has been carried out into the hydrogeology of Irish holy wells. The distribution of holy wells by geology and aquifer category was investigated using a GIS and by follow-up field surveys of more than 200 wells. It was found that holy wells are mainly shallow springs, and that they occur in all of the main lithological and aquifer groups. Water samples collected from 167 of these wells displayed a wide range of chemistries, influenced by geology, proximity to the sea and also by anthropogenic activities. There were very few statistically significant associations between chemical parameters and the reputed health cures associated with the wells, although elevated sodium and chloride levels were found in wells linked with eye cures (these eye wells were also found to be more common near the coast). Many holy wells have been covered over or subjected to unsympathetic developments over the years, and there is a need for greater protection, including the designation of more holy wells as County Geological Sites.

Key words: *Holy wells, groundwater chemistry, health.*

INTRODUCTION

This year's annual IAH Irish Group conference focuses on the 2022 UN World Water Day theme of "*Groundwater: Making the invisible visible*". The title reflects the fact that groundwater is a hidden resource, one that is often poorly understood and poorly managed. The aim of World Water Day and the accompanying UN World Water Development Report (UN Water, 2022) is to increase awareness amongst policy makers and other stakeholders about the role of groundwater in meeting demands for drinking water, agriculture, energy and other purposes, and to highlight its ecological importance in providing baseflows to rivers and in maintaining groundwater dependent ecosystems. With the large storage capacities of many of the world's aquifers, groundwater is likely to play a key role in combatting the vulnerability of surface water supplies to climate extremes, especially the longer and more frequent droughts that are forecast for the coming decades.

In addition to the provisioning, regulatory and supporting services provided by groundwater systems, groundwater also has a significant cultural role. The cultural services include mineral waters, spa waters and sacred wells, the latter being the subject of this short paper, which will summarise some of the findings of a 5-year study into the hydrogeology of Irish holy wells.

GROUNDWATER SOURCES

The aquifer sources of Irish holy wells were investigated in two main ways: a) an analysis of a National Monuments Service database of approximately 3,000 holy wells using a geographical information system (GIS), and b) field surveys of 215 holy wells.

The GIS analysis involved 2,676 geo-referenced wells, and examined their distribution according to physiography, bedrock geology, aquifers, groundwater vulnerability, etc. The physiographical and geological information was obtained from Geological Survey Ireland's online Groundwater Viewer. For the geological analysis, the numerous different formations and lithologies were combined into six main lithological groups - the same groupings used by Tedd *et al*. (2017) in their study of natural background levels of chemical parameters in Irish groundwaters. Figure 1 shows the percentage holy wells falling into the six main lithological groups compared with the percentage areas represented by these lithologies. It is evident that holy wells are found in all of the main lithologies, in approximate proportion to the areas represented. They are somewhat more common in the pure limestones and igneous terrains, and less so in the metamorphic rock areas.

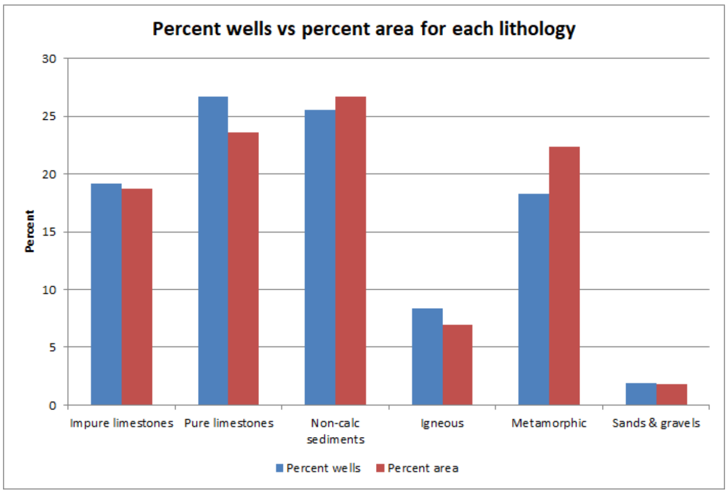

Figure 1: *Percent wells versus percent area of each lithological group (n = 2,569)*

In terms of aquifer categories, holy wells occur in all the classes, with higher frequencies in the regionally important fractured aquifers (Rf), conduit karst (Rkc) and locally important (Ll) classes (Figure 2). Overall, about 68% of the wells were located in the poorly productive categories (Ll, Pl and Pu), which occupy about 72% of the territory of the Republic of Ireland. We can conclude, therefore, that holy wells are almost as likely to be found in the poorly productive as in the more productive aquifers.

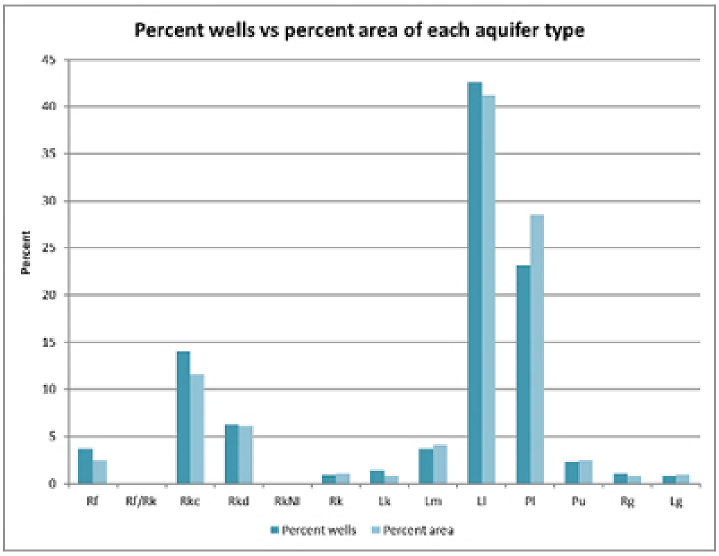

Figure 2: *Percent wells against percent area of each aquifer category (n = 2,614)*

The field surveys of more than 200 sites confirmed that the majority of holy wells are shallow springs and seepages, around which some form of well lining and housing has usually been constructed. With the exception of a few large karst springs (such as Tobernalt in County Sligo and the Ogulla well in County Roscommon), most of the springs and seeps at holy wells have very small flows (of the order of litres per minute).The wells are shallow, with an average depth of water of around 0.3 m.

There are a small number of deeper holy wells, including some that tap confined aquifers. Examples are Bride's well near Kilcock in County Meath (Dinantian upper impure limestones), and St Brigid's well near Newcastle West in County Limerick (Dinantian upper impure limestones underlain by Dinantian pure unbedded limestones).

WATER CHEMISTRIES

A total of 238 water samples were collected for analysis from 167 of the holy wells (plus five spa wells). These included duplicates and repeat samples, the latter generally where ion balance errors exceeded 10%. In addition, four wells of contrasting hydrogeology were selected for regular monitoring and sampling over a 2-year period. Some 60 parameters were measured, including a large number of trace elements (Table 1). The analyses were carried out in the Trinity College Dublin Geochemistry laboratory, the TCD Environmental Engineering laboratory and in two external laboratories (City Analysts Ltd and CAL Ltd). The physico-chemical parameters EC, pH and water temperature were measured on-site with a handheld meter.

Table 1: *Chemical parameters analysed in this research*

Category	Parameter
Main physico-chemical parameters	EC, pH, temperature
Major ions	Calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), alkalinity (HCO_3), sulphate (SO_4), chloride (Cl), nitrate (NO_3) [plus silicon (Si)]
Alkali metals	Lithium (Li), rubidium (Rb), caesium (Cs)
Alkali earth elements	Beryllium (Be), strontium (Sr), barium (Ba)
Metalloids	Arsenic (As), antimony (Sb)
Non-metals	Fluoride (F), phosphorus (P), selenium (Se)
Transition elements	Scandium (Sc), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), yttrium (Y), zircon (Zr), niobium (Nb), molybdenum (Mo), cadmium (Cd), hafnium (Hf), tantalum (Ta), tungsten (W)
Post-transition elements	Aluminium (Al), gallium (Ga), indium (In), tin (Sn), thallium (Tl), lead (Pb)
Lanthanide rare earth elements	Lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), terbium (Tb), gadolinium (Gd), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutelium (Lu)
Actinides (radionuclides)	Thorium (Th), uranium (U)

As might be expected, the holy wells displayed a wide range of water chemistries. The wells tapping the pure and impure limestone groups were dominated by calcium-bicarbonate waters (Figure 3). This was also the case for the wells in gravel (and in mixed bedrock and gravel) aquifers. The wells sourced from the non-calcareous sandstone, igneous and metamorphic aquifers had higher proportions of other major ions, including sodium and chloride. It was also found that sodium and chloride concentrations were elevated in those wells near the coast, where rainfall (and hence recharge waters) would be influenced by salt from sea spray.

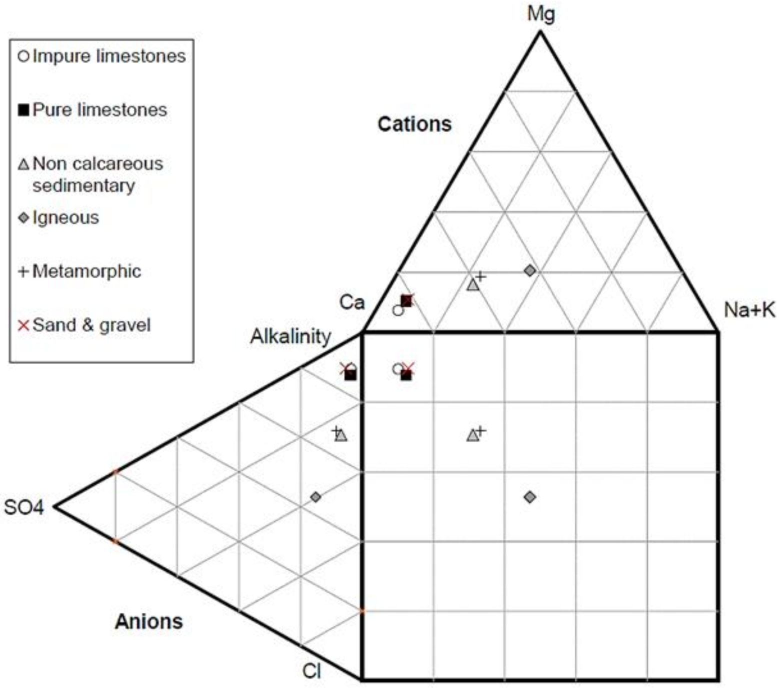

Figure 3: *Durov plot for the median ionic concentrations of the six main lithological groups*

The aquifer lithology also had a strong influence on the trace element water chemistry. To take one example, there were higher levels of strontium in the wells sourced from limestone rocks (Figure 4). The solubility of strontium is seldom reached in groundwaters and hence this element can provide a good indication of groundwater residence times. The higher strontium concentrations in the pure and impure limestone well samples therefore suggest longer flow paths and residence times in these aquifers compared to the igneous, metamorphic and non-calcareous sandstone lithologies (and also possibly greater availability of strontium minerals like strontianite and celestine).

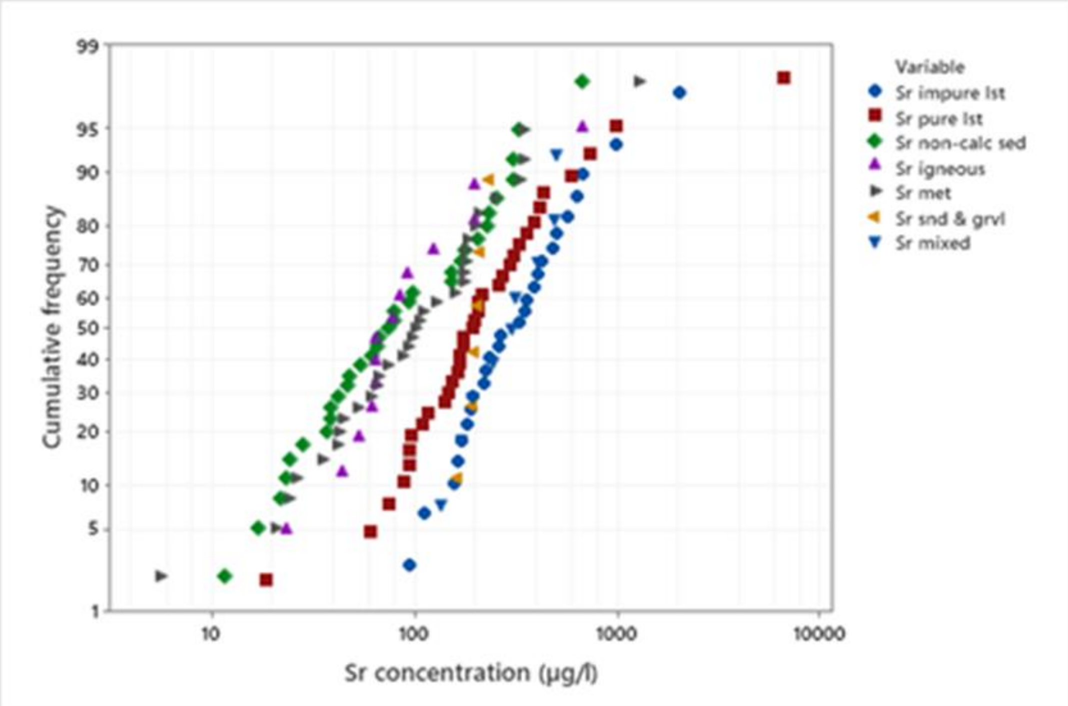

Figure 4: *Cumulative probability diagram of strontium concentrations in the different lithological groups*

An important finding with respect to water quality was that about half of the wells (52%) had nitrate levels above the natural background level of 2 mg/l as N (Tedd *et al*., 2017), although very few samples exceeded the drinking water standard of 11.3 mg/l as N. These results show that the shallow springs and seeps that form the majority of holy wells are potentially vulnerable to contamination.

HEALING REPUTATIONS

Many holy wells have reputations for healing. One study of holy wells in Britain and Ireland reported 75 different illnesses for which cures at holy wells have been linked (Bord and Bord, 1985). In the current study, reports of reputed cures were found for 57% of the wells surveyed and sampled. The most common reported cure was in connection with eye ailments (27% of the surveyed wells), followed by joint and various rheumatic ailments, toothaches and headaches, but many wells are associated with general, unspecified cures.

Statistical analyses were performed to see if there were any significant differences between the water chemistries of those holy wells associated with a particular cure, and the remaining wells. These tests (Mann-Whitney U tests for non-parametric data) were carried out for each chemical parameter and each reputed cure. In general, few significant differences were revealed. One exception was for sodium and chloride in the wells with healing reputations for eye cures, where the sodium and chloride levels were higher in the eye wells. However, it was also found that eye wells were more common near the coast (at least amongst those wells sampled), where elevated sodium and chloride values would be expected. It should be added here that the elevated concentrations are still relatively low in comparison to the likely values in the common medicated solutions used to treat eye irritations nowadays.

A final point about healing reputations: it should be remembered that the spiritual dimension of a holy well, including any rituals performed at the well, is likely to be an important factor in any therapeutic benefits to the believer.

HOLY WELLS: MAKING THE INVISIBLE VISIBLE

Holy wells are an important part of our cultural heritage. The majority of holy wells are designated as National Monuments, which should afford them some protection. However, the reality is that many holy wells have been lost, covered over or have been subjected to unsympathetic developments.

They are also important as cultural features of Irish hydrogeology. More wells should be designated as County Geological Sites, for inclusion in County Development Plans. Some of the most important could be considered for Natural Heritage Areas. These actions would provide them with additional protection.

The aim of this paper has been to highlight the hydrogeology of Irish holy wells, thereby helping to make them more visible to a wider audience. This aim is being pursued further with the publication of a book on this research, to be published by Geological Survey Ireland.

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